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AND SYMBOLIC IDENTIFICATION:

EFFECTS OF CODING, PRACTICE, RETENTION, AND TRANSFER

BY

AFOSR-TR- 89-0810

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Abstract

Research on stimulus-response compatibility effects is reviewed, with an integrated theoretical perspective provided that stresses mental coding of the stimulus and response sets. Eleven experiments, plus two follow-up experiments, are described in detail. The first six evaluate the nature of the codings used in spatial-precuing tasks. The remaining seven experiments examine the influence of practice on performance in the spatial-precuing tasks, as well as in symbolic-compatibility tasks. The experiments show that the codings used by subjects are affected by manipulations of the stimulus set but not of the response set. Compatibility effects within both tasks are reduced greatly by three sessions of practice. Transfer of these benefits to related tasks occurs in situations for which the response set is not altered. However, after more extended practice, partial transfer occurs even when the response set is changed. The results are interpreted in terms of an account that emphasizes salient-feature codings in a declarative stage of skill acquisition, with task-specific procedures acquired from practice.

A-1

I. Introduction

Models of human information processing distinguish between at least three basic stages: (1) stimulus identification; (2) stimulus-response translation; and (3) response or motor programming (Schmidt, 1988; Teichner & Krebs, 1974; Welford, 1976). These processing stages are considered to be affected primarily by stimulus characteristics, stimulus-response relations, and response characteristics, respectively (Schmidt, 1988). Although the speed and accuracy of responses can be influenced by all three of the basic processing stages, much interest in the human performance and human factors literature has focused on the translation stage (Fitts & Posner, 1967; Kantowitz, 1982; Kantowitz & Sorkin, 1983; Sanders & McCormick, 1987; Welford, 1976; Wickens, 1984). The importance of the translation stage is that it involves the processes by which an identified stimulus is related to an appropriate response (i.e., response-selection processes). As a consequence, the processing operations of the translation stage are directly affected by the specific assignments of stimuli to responses. Moreover, the translation requirements represent those aspects of a task that are most amenable to training and practice (Eberts, 1984; Schneider & Fisk, 1983). Because of these reasons, principles that underlie stimulus-response translation are of considerable importance in the design of human-machine interfaces.

Although much of the research in human experimental psychology, such as investigations of visual search and memory search (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977), can be viewed as examining S-R translation, the research that is of most direct relevance to applied concerns has examined <u>stimulus-response (S-R) compatibility</u>.

This term, introduced by A. M. Small in a paper delivered to the Ergonomic Research Society in 1951 (Small, 1989), was popularized in a classic study conducted by Fitts and Seeger (1953). These researchers examined nine stimulus-response ensembles involving all possible pairings of three spatial stimulus arrangements and three spatial response arrangements. Fitts and Seeger found that responses were faster and more accurate when the spatial properties of the stimulus set matched those of the response set. In other words, responding was faster with the compatible S-R arrangements, for which the stimulus display corresponded "naturally" to the response arrangement, than with incompatible arrangements.

S-R compatibility has been the subject of numerous investigations since Fitts and Seeger's seminal work. The present report (a) reviews contemporary research on S-R compatibility effects, (b) evaluates the nature of coding operations that underlie these effects, (c) examines the influence of practice on these operations, and (d) provides a theoretical framework that captures the primary empirical findings.

II. S-R Compatibility: An Integrated Perspective

Because the investigations of S-R compatibility have been conducted by researchers from diverse backgrounds, we edited a book in which the major researchers summarized their work and presented their perspectives regarding S-R compatibility effects (Proctor & Reeve, in press; see Appendix 1 for the table of contents and list of contributors). The theoretical review presented in this section is a modified version of our summary chapter from the book. This review is divided into a presentation of contemporary knowledge regarding compatibility effects and models of S-R compatibility.

Contemporary Knowledge Regarding S-R Compatibility

The rich history of research on S-R compatibility is documented by Small in the Foreword to the book and in introductory chapters by Alluisi and Warm (Chapter 1) and Simon (Chapter 2). As described by Small, contemporary interest in compatibility effects arose from the applied problems faced by human-factors engineers in designing military-related systems. Although Small's interest was primarily in stimulus-stimulus compatibility (e.g., relations between stimulus properties in multi-sensory displays), the research of Paul Fitts and his colleagues changed the emphasis to one of S-R compatibility. As indicated by Alluisi and Warm, considerable research on compatibility effects with light-patterned stimulus sets and motor response sets was conducted in the 1950s, not only by Fitts and his colleagues but also by David Grant, William Garvey, and their respective co-workers. These early studies demonstrated clearly the fact that, for spatial-location stimuli and responses, relative compatibility is primarily a function of the degree of direct physical correspondence. Another factor illustrated in the early studies was that compatibility is a function of the extent to which S-R pairings are consistent with population stereotypes (i.e., tendencies to make particular responses to stimuli in free response situations).

From these beginnings, research on S-R compatibility branched out to consider a variety of situations. Even when apparent physical correspondence was lacking, certain sets of responses could be executed faster and more accurately to a set of stimuli than could other sets of responses. For example, vocal number-naming responses could be made faster to numerical stimuli than could key-press responses (Alluisi &

Muller, 1958). In addition, when the spatial locations of stimuli were irrelevant to the task, these locations still were shown to produce compatibility effects. This latter phenomenon was an accidental discovery made by Simon (Chapter 2), which he subsequently investigated thoroughly. The phenomenon has come to be regarded as a distinct type of compatibility effect, now referred to as the "Simon effect." It reflects a basic response-selection tendency to react toward the source of stimulation. The implication of the Simon effect for system designers is that irrelevant location cues can interfere with human information processing.

Despite the substantial research conducted on S-R compatibility effects, until recently relatively little progress was made toward the development of detailed, theoretical accounts. However, in recent years, several research programs have focused on examining the nature of compatibility effects, with these programs collectively providing new insight into the mechanisms that underlie S-R compatibility. Although these research programs are diverse, they can be categorized broadly as examinations of mental representations, psychophysiological indices and neurophysiological mechanisms, the relation of S-R compatibility to motor performance, and applications to human factors.

Mental Representation

Studies of the role of mental representation in S-R compatibility have focused primarily on "coding" explanations. Such explanations have been developed because, as Alluisi and Warm (Chapter 1) emphasize, compatibility effects are a function of the extent to which "pairings of stimulus and response alphabets correspond to one another in a direct *conceptual* sense." That is, compatibility is not merely a function of physical correspondence, but of a correspondence between abstract mental codes that are formed to represent the stimulus and response sets.

Because many studies of S-R compatibility have used spatial-location stimuli and responses, emphasis has been placed on spatial coding. With the most widely used procedure, the subject responds to one of two stimuli by making a discrete key-press response with either the left or right index finger (Simon, 1969; Wallace, 1971). The basic compatibility effect obtained in this situation is that responses are faster and more accurate if the left and right stimulus locations are assigned to the left and right response locations, respectively, than if the assignments are reversed (Anzola, Bertolini, Buchtel, & Rizzolatti, 1977; Brebner, 1973; Brebner, Shepard, & Cairney, 1972).

Among the earliest demonstrations in support of a spatial-coding account were those provided by Wallace (1971, 1972). He dissociated spatial locations from response effectors by having subjects perform a two-choice task with the arms crossed. The crucial outcome was that the fastest responses still occurred when the right light signaled the right response location and the left light signaled the left response location. Thus, Wallace concluded that the compatibility effect was due to spatial coding of the stimulus locations and not to the relation of the stimulus locations to the left and right hands.

Subsequent to Wallace's (1971, 1972) finding, the nature of spatial coding and the way in which such coding influences responding have been examined in detail. Umilta and Nicoletti (Chapter 3) note that when the stimulus and response sets are composed of left and right elements, the designation "left" and "right" refers to both egocentric and relative locations. Umilta and Nicoletti unconfounded these two location dimensions from the stimulus set and found that each independently produced S-R compatibility effects. For the response set, the egocentric dimension has yet to be evaluated, but compatibility effects have been demonstrated that are attributable to the relative position of the response. Moreover, distinguishing between the relative position of the effector and the relative position of the response goal showed that S-R compatibility effects are a function of the latter. Other research by Umilta and Nicoletti demonstrated that compatibility effects can be obtained for the above-below dimension, as well as for the left-right dimension, but that the latter dimension dominates when the stimulus and response sets overlap in both dimensions. Umilta and Nicoletti conclude that spatial compatibility effects produced by a relevant location dimension reflect the time for translation between stimuli and responses, whereas spatial compatibility effects produced by an irrelevant location dimension (i.e., the Simon effect) most likely reflect competition in the selection of the appropriate response.

Heister, Schroeder-Heister, and Ehrenstein (Chapter 4) show that similar evidence for spatial coding is obtained when subjects respond with two fingers from a single hand, either prone or supine. They distinguish between spatial finger distance and anatomical finger distance, finding that spatial distance is crucial, as would be expected by a spatial-coding account. In addition, Heister et al. report evidence for "spatio-anatomical mapping," which involves internal coding of anatomical left-right classifications. Heister et al. propose a model in which coding of key position, coding of effector position, and spatio-anatomical mapping are arranged in an interactive hierarchy.

Ladavas (Chapter 5) also supports a hierarchical model similar to that proposed by Heister et al. She emphasizes that whereas spatial coding dominates in most situations, the anatomical status of the responding hand becomes important when there is no dimensional overlap between stimulus and response locations. Moreover, Ladavas shows the presence of spatial compatibility effects in young children who have not yet acquired the capacity to label left and right. Thus, spatial S-R compatibility effects apparently are not a consequence of verbally labeling the positions of stimuli and responses.

Reeve and Proctor (Chapter 6) report further evidence for spatial coding in more complex, four-choice spatial-precuing tasks. In such tasks, differential precuing benefits for particular pairs of responses are a function of the spatial locations that are cued and not of whether the fingers are from the same or different hands. Similar evidence for spatial coding is apparent when two-dimensional, symbolic stimuli are assigned to the four response locations. Additionally, with both spatial-location and symbolic stimuli, evidence for hand coding is obtained when the distinction between the hands is made salient. Reeve and Proctor propose that their findings are captured by a salient-features coding principle, according to which the relative reaction times (RTs) are a function of the extent to which the salient features of the stimulus set and the salient features of the response set correspond.

Psychophysiological Indices and Neurophysiological Mechanisms

Other researchers have related the compatibility effects that are observed for RTs to psychophysiological indices and have examined the neurophysiological bases for the effects. Most of the psychophysiological research has examined event-related potentials (ERPs). Bashore (Chapter 7), Ragot (Chapter 8), and Brebner (Chapter 9) summarize evidence that these indices of cerebral activity provide information that is not redundant with the RT measure and that can be used to distinguish between alternative accounts for compatibility effects.

The psychophysiological research has focused primarily on the P300 wave. The P300 latency has been shown to be influenced strongly by stimulus processing. The evidence regarding whether the P300 is affected by response-selection processes is far less clear. Some studies have found little or no effect of such processes on the P300 latency, whereas other studies have shown stronger effects. For example, Coles, Gratton, Bashore, Eriksen, and Donchin (1985) found that the latency of the P300 was increased when flanking noise letters signaled a response that was incongruent with the response indicated by a target letter. Bashore (Chapter 7) describes a study in which S-R compatibility was manipulated in the flanker task by using different assignments of left- and right-pointing arrows to responses. P300 latency was influenced by both target-noise incongruity and S-R compatibility, and the latency of another component, the N200, was affected only by S-R compatibility. Bashore notes that the P300 latency was not influenced by S-R compatibility when the flanking noise stimuli were neutral asterisks. Thus, his results imply that S-R compatibility affects P300 latency only for situations in which stimuli activate competing responses.

Ragot (Chapter 8) describes research from his laboratory that leads to a similar conclusion. He summarizes several studies in which the P300 was found to be delayed by spatial incompatibility when stimulus location was irrelevant (i.e., the situation in which the Simon effect is obtained). Ragot concludes that the distinguishing factor between studies that obtained an effect of S-R compatibility and those that did not is whether an incongruent response is indicated by an irrelevant stimulus dimension. Thus, the ERP studies suggest that the P300 is sensitive to response competition effects and that the basis of the Simon effect is similar to that of the flanker interference.

Brebner (Chapter 9) examines individual differences in the P300 latency, noting that introverts and extroverts differ on this measure. Introverts have much shorter P300 latencies than do extroverts, yet their RTs are longer. This pattern of results is consistent with a model of introversion/extroversion developed by Brebner and Cooper (1974). According to the model, introverts derive excitation from stimulus analysis and inhibition from response organization, with extroverts showing the opposite relation. Brebner's findings suggest that individual differences play an important role in compatibility effects and that psychophysiological measures may be useful in resolving the nature of the differences.

Speculation about the neurophysiological basis of S-R compatibility effects has taken two forms. First, compatibility effects have been used as estimates of interhemispheric transmission time (Bashore, Chapter 7). The logic, articulated initially by Poffenberger (1912), is that RTs should be shorter if both the reception of the stimulus and the execution of the response occur within the same hemisphere, because cross-commissural communication is not required. However, Bashore summarizes evidence indicating that anatomical connectivity is not the primary determinant of compatibility effects in choice-RT tasks. That is, in choice tasks, spatial-locations are crucial, rather than the particular effector. For simple RT, a small effect of anatomical connectivity does seem to be obtained reliably, with the resulting estimate of interhemispheric transmission time being 1-3 ms.

Verfaellie, Bowers, and Heilman (Chapter 10) provide an alternative neurophysiological account for the compatibility effects that are obtained in choice-RT tasks, because the interhemispheric account is not able to explain the data from these tasks. Verfaellie et al.'s hypothesis is that each hemisphere controls different aspects of attention in contralateral hemispace. When stimulus processing and response selection are mediated by the same hemisphere, RTs will be faster than when these processes are mediated by different hemispheres. Verfaellie et al. report performance data both for patients with hemispatial neglect and for normal subjects. These data suggest that in a free-field situation, each hemisphere directs attention and intention toward the contralateral side of space. When stimuli are presented to one side of space, the relative location is crucial, with the more lateral stimulus favored by the contralateral hemisphere. Verfaellie et al. report an experiment examining the Simon effect, in which either the location of the stimulus (attentional set) or location of the response (intentional set) or both were cued. Compatibility effects were obtained for valid-cuing trials only when attentional information was provided. Verfaellie et al. interpret these and other results as suggesting that intentional set primes the hemisphere that controls the cue processing, thus inducing compatibility effects as a function of whether the stimulus location is in the hemispace attended by the activated hemisphere. These authors conclude that the process by which responses are prepared is an important factor in S-R compatibility.

S-R Compatibility and Motor Performance

Studies that explicitly investigated the role of S-R compatibility in motor performance have been concerned primarily with controlling compatibility effects, so that motor-programming effects could be studied. Zelaznik and Franz (Chapter 11) emphasize that S-R compatibility effects are pervasive in such studies. The effects influence the patterns of RTs obtained for precuing various movement parameters when spatial incompatibility is present, as well as when symbolic stimuli are mapped arbitrarily to responses. Similarly, when comparing across S-R sets of different sizes, compatibility is a confounding factor. When the S-R assignment is incompatible, decreases in RT can occur simply as a function of a reduction in set size. Zelaznik and Franz propose that an operational test of whether S-R translation processes or motor-programming processes are determining the patterns of RTs is to manipulate S-R compatibility along with whether the precued movement parameters vary from trial-to-trial or are fixed. If the ordering of RTs is different for the varied and fixed methods, then the precued variables are influencing translation processes, as well as possibly motor processes. Only if the ordering is the same across methods can the results be interpreted relatively unambiguously in terms of motor processes.

Spijkers (Chapter 12) demonstrates the distinction between response selection and motor programming by showing the independence of compatibility effects from movement-precuing effects. In his experiments, neither spatial compatibility nor semantic compatibility affected the influence of average movement velocity on RT. Spijkers thus concludes that the response codes selected in the translation stage are abstract, nonmotoric representations. Motor programming then involves elaboration of the specific parameters of the movement.

Heuer (Chapter 13) also shows the independence of S-R compatibility effects and motor-programming effects, demonstrating that, unlike S-R compatibility effects, response-response (R-R) compatibility effects (differences in responding as a function of the alternative members of the response set) arise in motor programming. When different movements, rather than the same movements, are assigned to the two hands, a triad of R-R compatibility effects is observed: mean RTs are longer, mean RT variability is larger, and frequency of choice errors is less. However, these effects do not occur when the movements are the same, but the fingers with which they are executed are different. These R-R compatibility effects are attributed by Heuer to interactions that occur during the processes involved in simultaneously programming two responses.

Whereas most studies of S-R compatibility emphasize central, cognitive functioning, Gordon (Chapter 14) provides a special case of compatibility in speech perception and production that arises from low-level links between the perceptual and motor systems. He reports two experiments in which perceptual-motor interactions are shown for both the nasal/stop consonant distinction and the nasal/fricative distinction. Gordon concludes that such interactions occur only for features that are perceptually salient and presents an interactive-activation model to account for the effects.

Application to Human Factors

S-R compatibility has a pervasive influence in "real-world" situations, as shown by numerous examples provided by Kantowitz, Triggs, and Barnes (Chapter 15). These authors summarize a variety of types of S-R incompatibilities found in everyday life. They distinguish between types of incompatibility that arise from frames (general knowledge used to interpret experience), rules (relatively specific knowledge about simple S-R relations), and response tendencies (more specific tendencies for stimuli to elicit implicit responses). Kantowitz et al. stress the importance of developing models that relate the basic, laboratory findings to applied settings.

Eberts and Posey (Chapter 16) present such a model. They elaborate the concept of stimulus-central processing-response (S-C-R) compatibility proposed by Wickens and his associates (e.g., Wickens, Sandry, & Vidulich, 1983). Whereas Wickens stressed the nature of the mental code (spatial/verbal) required to perform a task, Eberts and Posey emphasize the structure of the mental model. They note that the mental model is dependent on the training of the operator and may change over time and that several analysis techniques exist for extracting the nature of the mental model. Eberts and Posey provide examples of how to improve S-R compatibility once the structure of the mental model has been identified. The authors emphasize the importance of designing the environment to be compatible with good mental models.

John and Newell (Chapter 17) present another model intended to relate basic findings to applied settings. Their model is based on a theory of S-R compatibility by Rosenbloom and Newell (1987) that is cast in terms of Goals, Operators, Methods, and Selection (GOMS) rules within the Model Human Processor (MHP) framework (Card, Moran, & Newell, 1983). Their analysis relies on the view that different mappings of stimuli to responses result in different sets of algorithms for accomplishing the task. John and Newell derived parameter estimates from an experiment examining the recall of computer command abbreviations. These parameters, and parameter estimates from Card et al. (1983), then were used to predict performance in four different types of S-R compatibility tasks. The average absolute percent errors between predictions and observations was 18.8%. The authors illustrate the potential use of the model by applying it to hypothetical design situations.

Summary

Several general points of consensus emerge from the chapters, including the following:

1. S-R compatibility effects are ubiquitous. They occur in a wide variety of situations, from basic perceptual-motor tasks to highly complex programming tasks.

2. Conceptual correspondence, rather than physical correspondence, is the source of S-R compatibility effects. Compatibility effects have been shown for stimulus sets and response sets that have no spatial-location dimension, for symbolic stimuli assigned to keypress responses, and for different pairs of cued responses within spatially compatible stimulus and response sets.

3. For spatial-location stimuli assigned to responses at different locations, compatibility effects occur regardless of whether the stimulus location is relevant or irrelevant for determining the correct response. Whether these two types of compatibility effects have similar bases is less clear.

4. S-R compatibility effects arise primarily from a stage of information processing that is referred to as the translation stage or the response-selection stage. These effects are independent from effects of R-R compatibility that arise in a response-programming stage.

5. The codings of stimulus and response sets, and how the codings relate, play an important role in most S-R compatibility effects. The nature of the codings determine how quickly and accurately a stimulus

code can be translated into a response code.

6. The coding system is hierarchical, but flexible. In most situations for which spatial-location stimuli are assigned to spatial-location responses, relative location coding dominates. However, spatio-anatomical mapping (e.g., the distinction between the left and right hands) dominates when it relates systematically to the salient stimulus feature but the response locations do not.

Models of S-R Compatibility

Traditionally, most models of S-R compatibility are characterized as providing "attentional" or "coding" accounts. A third category of models can be described as providing "general information processing" accounts. The present section compares and contrasts the various models of S-R compatibility, with the intent of emphasizing the points of agreement and disagreement.

Attentional Models

The attentional models originated with Simon's (Chapter 2) research on the influence of irrelevant spatial locations. These models emphasize the direction of attention to locations. Simon's initial account proposed an innate tendency to react in the direction of a stimulus. The buffer model that he has favored recently is a more elaborative account that describes the response-selection process as involving a scanning of response buffers. According to the model, a response buffer is established for each assigned response in a choice-RT task. Thus, for two-choice tasks that use left-hand and right-hand responses, two buffers are established that each contain a representation of the assigned stimulus. The buffers are assumed to be searched in a serial order when a stimulus is presented, with a response being initiated when a match is found. The irrelevant location of the stimulus affects responding by biasing the subject to search first the buffer of the corresponding location. According to Simon, this buffer model differs from the coding accounts in minimizing the cognitive component of S-R compatibility and stressing a more primitive response tendency, with this tendency being a function of relative location, rather than absolute location.

Verfaellie et al. (Chapter 10) relate the tendency to respond in the direction of the stimulus to activation of the corresponding hemisphere of the brain. According to them, the intention to execute a response in one hemispace produces activation in the contralateral hemisphere. This activation then facilitates the processing of a stimulus that occurs in the same hemispace.

One finding complicates explanations of the Simon effect in terms of an automatic tendency to respond in the direction of the stimulus. This finding is that the effect occurs when the two stimulus and response locations are to the same side of body midline (Umilta and Nicoletti, 1985; Chapter 3). Simon concludes that this finding does not really create a problem for the attentional account, but he does not provide an explicit explanation of the finding. Verfaellie et al. (Chapter 10) do consider more explicitly how an attentional account can explain the fact that the Simon effect occurs when the alternative locations are to the same side of the body midline. They present evidence that the more lateral stimulus is preferred by the contralateral hemisphere and the less lateral stimulus is preferred by the ipsilateral hemisphere, in such situations. Thus, Verfaellie et al. conclude that the control of attention by the hemispheres is dynamic, rather than being a fixed function of a strict spatial dichotomy.

Coding Models

Most authors who favor coding models view them as being complete explanations of compatibility effects that are not mediated by attentional factors. Umilta and Nicoletti (Chapter 3) have obtained evidence explicitly intended to rule out attentional accounts. In place of such accounts, they propose that spatial compatibility effects, both when stimulus locations are relevant and irrelevant, are due to the mental codes used to represent the relative positions of the response keys and/or the positions of the effectors.

Heister et al. (Chapter 4), Ladavas (Chapter 5), and Reeve and Proctor (Chapter 6) are in agreement with Umilta and Nicoletti that relative spatial coding is crucial to spatial-compatibility effects. In addition, they conclude that spatio-anatomical mapping is evident in certain circumstances. Thus, coding is viewed as hierarchical, with spatial coding being dominant and anatomical coding being used either when spatial coding cannot be or when the anatomical feature is made more salient.

Even within spatial coding, there seems to be a hierarchy of preferred codes. Umilta and Nicoletti indicate that above/below coding is used when it is the only dimension, whereas left/right coding dominates when stimuli could be coded on either dimension. Similarly, Reeve and Proctor note that within precued stimulus displays, a hierarchy exists for the relative precuing benefits that occur for the alternative pairs of precued locations. The benefit is greatest when the two leftmost or two rightmost locations are cued, intermediate when the two inner or two outer locations are cued, and least when either pair of alternating locations is cued.

Whereas the primary evidence for the coding model comes from spatial-location stimulus and response sets, evidence also has been obtained when the stimuli are symbolic. Differences in RT occur as a consequence of the assignment of the features of two-dimensional, symbolic stimuli to response locations (Reeve & Proctor, Chapter 6). Responses are faster and precuing benefits greater when the salient features of the stimulus and response sets correspond. Similarly, for auditory speech stimuli and vocal responses, the responses are faster when they share salient phonetic features with the stimuli than when they do not (Gordon, Chapter 14).

General Information-Processing Models

The third category involves models that have been developed by human-factors engineers to enable consideration of S-R compatibility in the design process. These models have as a goal the ability to predict performance in a variety of real-world settings. As a consequence, they explain compatibility effects within the context of more general models of human-information processing.

As discussed previously, Kantowitz et al. (Chapter 15) distinguish between compatibility effects that arise from frames, rules, and response tendencies. They emphasize that the effects that arise as a function of frames and rules are of most concern in human factors, but the majority of laboratory research has focused on effects at the level of response tendencies. An integrated model of S-R compatibility must consider all levels.

Eberts and Posey (Chapter 16) note that Wickens et al. (1983) took an initial step toward addressing the higher level determinants of compatibility in proposing their S-C-R compatibility model. Wickens et al. recognized the important fact that stimuli had to be incorporated into and retained by the mental models of the operators of complex machines. The S-C-R compatibility model thus emphasizes the importance of the code of central representation in compatibility effects. According to the model, the code can lie on a visual-verbal continuum. By knowing the nature of the central code, input displays and response devices can be designed to be consistent with the code.

Eberts and Posey build on the S-C-R compatibility model by changing the emphasis from the nature of the mental code to one of the structure of the mental model of the operator. That is, the mental model is the conceptual representation of a system that the operator has acquired from the system documentation and from interaction with the system. In Eberts and Posey's account, several structures can be used for the mental models: (a) image-based spatial mental models; (b) frame-based mental models; (c) production systems; and (d) goal hierarchies. Good and bad mental models, which lead to good or bad performance, are dependent on the perceived consistencies in the task. The mental model approach enables the development of techniques to determine the structure of the mental model for a task and, thus, specification of the methods to improve S-R compatibility.

John and Newell's (Chapter 17) engineering model is based on the GOMS theory of Rosenbloom and Newell (1987) that was developed within a general model of cognition, the MHP (Card et al., 1983). The MHP model specifies three separate processors: a perceptual processor, a cognitive processor, and a motor processor. The basic procedure of an MHP analysis is to determine the gross functions and elementary operations that each processor must take in order to perform a task. Each elementary operation is assigned a duration (through an estimation procedure), thus enabling prediction of response times for different tasks.

John and Newell estimated the operator durations from a task involving human-computer interaction. Compatibility was varied by the directness with which the commands related to the actions that were to be performed. The predictions of the GOMS model fit the results relatively well. Moreover, using the same set of estimated operator durations, the model predicted relatively accurately the response times in (a) a second command abbreviation experiment, (b) two spatial-compatibility studies, and (c) a study requiring a visual number-naming response to either numeric stimuli or to nonalphanumeric forms. Thus, the GOMS model is able to make relatively accurate predictions across a wide range of tasks.

Summary

Most of the models of S-R compatibility rely on mental coding. These models explain S-R compatibility effects in terms of the mental representations used to perform the tasks. The representations determine the duration of processing that must be performed and, hence, RT. Considerable evidence for coding accounts has been gathered from tasks that range from phoneme identification to choices between spatial-location stimuli and responses, to computer programming. Moreover, considerable progress has been made in determining the nature of the codes and the situations in which particular types of codings will be used. Most interestingly, the results from simple perceptual-motor tasks seem to be explainable in terms similar to the results from much more cognitively complex, human-machine interactions. In short, the coding operations revealed by studies of S-R compatibility seem to reflect fundamental cognitive processes of broad generality.

At present, attentional models are not as widely accepted as are coding models. The primary evidence for attentional mechanisms comes from the Simon effect. Yet, even for that effect, the evidence implicates flexible control, rather than a fixed tendency to respond toward a source. If a tendency to attend to particular locations is needed to augment the coding accounts, as Simon (Chapter 2) and Verfaellie et al. (Chapter 10) argue, this attentional control also must be based on cognitive representations of the task.

An Integrated Perspective

Despite the diversity of S-R compatibility phenomena, research is converging on specific underlying mechanisms and common explanatory principles. The most consistent point that emerges from the chapters is that compatibility effects reflect basic cognitive processes that influence human performance in a variety of situations, ranging from simple perceptual-motor tasks to complex cognitive tasks. Performance is a function of the manner in which the alternative stimuli and responses are mentally represented. These representations are based on salient features of the stimulus and response sets. The rate of translation between the stimulus and response representations determines relative compatibility, with compatible situations being those for which the correspondence between codes is most direct.

The more than 30 years of research on S-R compatibility has produced a substantial body of data. Although a theoretical explanation of compatibility phenomena has been slow in coming, the understanding of the phenomena has increased substantially. For example, the knowledge now has attained a level at which it is possible to predict with reasonable accuracy the relative compatibilities in seemingly unrelated situations. Perhaps more importantly, the understanding has emphasized the central role of compatibility in human-information processing. That is, because S-R compatibility phenomena arise primarily from translation processes that mediate between perceptual representations and motor representations, the phenomena provide important evidence regarding the representations and operations that underlie human cognition.

III. Empirical Research

In this section, we present experiments that pertain to two related areas of inquiry. The first area provides the results of five experiments that examine the coding of stimulus and response sets by manipulating the salient characteristics of each. The second area includes the results of six experiments that examine the retention and transfer of benefits obtained through practice.

General Methods

The experiments used variations of a response-precuing procedure (Miller, 1982; Rosenbaum, 1983; Proctor & Reeve, 1986; Reeve & Proctor, 1984) to investigate S-R compatibility. The unique feature of the precuing procedure is that advanced information regarding the possible responses can be presented on a trial, thus reducing the number of response alternatives. The primary advantages of the procedure are that (a) it allows the use of relatively complex S-R situations, and (b) it has considerable flexibility, allowing precise manipulations of both stimulus and response characteristics.

The general methods are described in detail in the remainder of this section. Deviations from the general methods are indicated for the specific experiments. Standard control procedures, such as counterbalancing for order and random assignment to conditions, were followed for all experiments.

Apparatus and Stimuli

Stimuli were presented on the display screen of a microcomputer and were viewed from a distance of approximately 50 cm. Discrete responses were made by pressing one of four permissible keys on the computer's keyboard. Stimulus durations and intervals were controlled by the computer. The computer also recorded the specific stimulus conditions, the response key that was pressed, and the time between the target onset and the response (RT).

The stimulus display for each trial consisted of a warning stimulus, a precue stimulus, and a target stimulus, with the entire display centered on the viewing screen. The warning stimulus was a row of four plus signs. Each sign was approximately 3 mm square, with a blank space of 6 mm separating each sign in the row. The precue occurred immediately below the warning stimulus and consisted of plus signs either in all four of the positions occupied by the warning stimulus or in only two of the four positions. The target was a single plus sign that occurred immediately below one of the cued positions. The warning, precue, and target rows each were separated by 5 mm.

The subject's task was to indicate the position in which the target occurred by making a discrete finger response with either the left-middle, left-index, right-index, or right-middle finger. The assignments of fingers to response locations and the placement of the hands depended on the specific situations being investigated.

Four precuing conditions comparable to those from previous studies were used (Proctor & Reeve, 1986; Reeve & Proctor, 1984). These conditions differed in terms of the responses indicated by the precue. Examples of each condition are shown in Table 1 for a left-hand, middle-finger response. For the unprepared condition, the precue contained all four plus signs, and the target occurred in any of the four positions. For the three prepared conditions, the precue contained only two plus signs, and the target occurred in one of these two positions. In the prepared:hand condition, the precue indicated the two positions assigned to either the left or right hand. In the prepared:finger condition, the precue specified the two positions assigned to either the index or middle fingers. In the prepared:neither condition, the precue indicated positions assigned to the index finger for one hand and the middle finger for the other hand.

Insert Table 1 about here

In addition to the type of cue, the interval between precue onset and target onset was varied. Previously, we demonstrated that with sufficient time (3 s), all combinations of responses can be prepared equally well. However, at shorter precuing intervals, compatibility effects are evident (Reeve & Proctor, 1984). The precuing intervals for the present experiments were varied between 0 s (i.e., simultaneous onset of the precue and target) and 3 s, to encompass the critical range.

Subjects and Procedure

Subjects were students enrolled at either Auburn University or Purdue University, who participated for extra credit or to satisfy a course requirement. Each subject received specific instructions regarding the nature of the experiment and signed a consent form. S-R assignments typically were manipulated between subjects, whereas precuing conditions and intervals were manipulated within subjects. Each subject participated in one or more sessions of 240 to 320 trials, depending on the requirements of the particular experiment.

A Systematic Examination of Coding Operations

This component of the project explored implications of the salient-features coding principle (Proctor & Reeve, 1986). According to this principle, compatible situations are produced when a correspondence occurs between the salient features of the stimulus set and the salient features of the response set. The principle was developed from experiments that used both spatial and symbolic stimuli (Proctor & Reeve, 1985, 1986; Reeve & Proctor, 1984). However, the experiments involved manipulations of the assignments of the stimulus sets and response sets, without altering the features of the respective sets. The experiments in this section used manipulations of the features of the stimulus and response sets to determine whether these manipulations influence the coding operations in a manner consistent with the salient-features coding principle. The experiments also provide evidence regarding the nature of the translation processes that rely on the codes.

Experiment 1: Altering the Salient Features of the Stimulus Set

When a horizontal stimulus set is used, subjects code the stimuli according to the salient left-right feature of the set. This coding produces an advantage for precuing the two leftmost or two rightmost locations (Reeve & Proctor, 1984). By manipulating the characteristics of the stimulus set, it may be possible to alter the features such that other subsets of cued locations become relatively more salient. If such manipulations are effective, the precuing benefits typically observed for the left or right spatial locations also should occur for the locations that correspond with the features that have been made more salient.

The stimulus display used in Experiment 1 was a modification of the horizontal arrangement described in the General Methods. The four locations were indicated either by "+" or "o" characters. In the control displays, the same character was used for all four locations. In the experimental displays, two instances of each of the two characters were used to designate the four locations. The use of two characters allows pairs of locations that share a common character to be grouped according to the Gestalt principle of similarity (Kaufman, 1974). Thus, the experiment evaluated whether similarity grouping influences the coding of the stimulus and response sets.

The four types of stimulus displays that were used are presented in Table 2; the two versions of each display type that are produced by switching the locations of the "+" and "o" characters are shown. For the left-right display, the grouping of stimulus characters by similarity is consistent with the left-right distinction of the stimulus display. For the inner-outer display, the grouping of stimulus characters is consistent with the distinction between the two inner and two outer locations. For the alternating display, the grouping of stimulus characters is consistent with the distinction between alternating locations.

Insert Table 2 about here

The four stimulus displays were used with both adjacent and overlapped hand placements. For the adjacent placement, the two hands were placed together on the bottom row of the keyboard, with the left-middle, left-index, right-index, and right-middle fingers on the **V**, **B**, **N**, and **M** keys, respectively. For the overlapped placement, one hand was placed over the other, with the fingers alternated, so that the assignment of fingers to the **V**, **B**, **N**, and **M** keys was right-index, left-middle, right-middle, and left-index, respectively. As shown by Reeve and Proctor (1984), the two hand placements allow dissociation of the hand and spatial-location features of the response set.

Because the left-right spatial feature is salient for the horizontal stimulus and response arrangements, the typical benefit for precuing the left or right pairs of locations should be obtained for all displays. Moreover, for the displays in which the similarity grouping emphasizes another feature in addition to the left-right feature (i.e., the inner-outer and alternating displays), similar precuing benefits should occur for other pairs of precued locations.

Method. One-hundred and twenty-eight subjects were tested, 64 with the adjacent hand placement and 64 with the overlapped placement. Within each of these groups, 16 subjects were tested with each of the four display conditions: (a) the control display (all four stimulus elements the same, either "+" or "o" signs); (b) the left-right display, for which the two leftmost elements were of one type and the two rightmost elements of the other; (c) the inner-outer display, for which the two inner and two outer elements were of different types; and (d) the alternating display, for which alternate elements differed in type. For all display conditions, half the subjects received Version 1, and half received Version 2 (see Table 2). In other respects, the method was as described in the General Methods section.

Results. The RT data showed main effects of precue, $F(3, 360) =$

26.7, $p < .001$, and interval, $F(4, 480) = 359.4$, $p < .001$, as well as a Precue x Interval interaction, $F(12, 1344) = 12.0$, $p < .001$. The precue main effect is due primarily to responses being faster for the prepared conditions (Ms = 594, 596, and 598 ms for the prepared:hand, prepared:finger, and prepared:neither conditions, respectively) than for the unprepared condition ($M = 622$ ms). The interval effect reflects a decrease in RT as the precuing interval increased (Ms = 697, 611, 596, 562, and 550 ms for the intervals of 0, 375, 750, 1500, and 3000 ms, respectively). The interaction is due to the advantage for the prepared conditions, relative to the unprepared condition, increasing across precuing intervals. All three of these effects customarily are obtained with the precuing procedure (e.g., Proctor & Reeve, 1986, 1988; Reeve & Proctor, 1984). They are present in all of the spatial-precuing experiments described in this report, but will not be discussed in detail for the subsequent experiments.

The main effect of hand placement also was significant, $F(1, 20) = 117.3$, $p < .001$, with responses being slower for the overlapped placement ($M = 693$ ms) than for the adjacent placement ($M = 512$ ms). Hand placement interacted with precue, $F(3, 360) = 19.4$, $p < .001$, and with precue and interval, $F(12, 1344) = 3.07$, $p < .001$. The interaction with precue replicates the finding of Reeve and Proctor (1984) that the precuing benefits are determined by the spatial locations. For both hand placements, RTs were slowest for the unprepared condition (Ms = 533 and 711 ms). However, the ordering of the prepared conditions was different for the adjacent placement than for the overlapped placement. For the prepared:hand, prepared:finger, and prepared:neither conditions, the means were 488, 507, and 521 ms for the adjacent placement and 699, 686, and 676 ms for the overlapped placement. Because the pairs of locations that correspond to the prepared:hand and prepared:neither conditions are switched for the two hand placements, the RTs are ordered consistently by the precued locations. The three-way interaction with interval is a function of the differences between the prepared conditions being evident primarily at the shorter intervals.

Of most interest was the factor of display condition. The only term involving this factor that was significant is the main effect, $F(3, 120) = 2.90$, $p < .05$. This effect reflects slower responses for the control display ($M = 626$ ms) and the alternating display ($M = 624$ ms) than for the left-right display ($M = 592$ ms) and the inner-outer display ($M = 567$ ms). Moreover, the pattern of RTs for the alternating display was similar to that for the control display (see Table 3).

Insert Table 3 about here

A follow-up analysis was performed to compare the left-right and inner-outer displays. This analysis showed a nonsignificant main effect of display condition, but a marginally significant interaction of Display x Precue x Hand Placement, $F(3, 180) = 2.46$, $p = .06$ (see Table 3). With the adjacent hand placement, the two display conditions differed by only 14 and 16 ms for the unprepared and prepared:hand conditions, respectively. However, for the prepared:finger and prepared:neither conditions, responses were approximately 35 ms faster with the inner-outer display than with the left-right display. With the overlapped placement, the smaller differences were obtained for the unprepared (10 ms) and the prepared:neither (8 ms) conditions, with RTs for the prepared:hand and prepared:finger conditions being 42 and 35 ms faster, respectively, with the inner-outer display than with the left-right display. Thus, relative to the left-right display, the inner-outer display increased the precuing benefits for the inner-outer and alternating precue locations, regardless of hand placement.

The analysis of errors showed main effects of precue, $\underline{F}(3, 360) = 19.1$, $\underline{p} < .001$, hand placement, $\underline{F}(1, 120) = 13.0$, $\underline{p} < .001$, and interval, $\underline{F}(4, 480) = 3.64$, $\underline{p} < .01$. More errors were made (a) for the prepared conditions (4.9%, 5.2%, and 5.7% for the prepared:hand, prepared:finger, and prepared:neither conditions, respectively) than for the unprepared condition (3.0%), (b) with the overlapped placement (6.6%) than with the adjacent placement (2.9%), and (c) at intermediate intervals (4.5%, 5.4%, 4.9%, 4.3%, and 4.5% for the intervals of 0, 375, 750, 1500, and 3000 ms, respectively).

Additionally, the two-way interactions of Hand Placement x Precue, $\underline{F}(3, 360) = 12.6$, $\underline{p} < .001$, and Hand Placement x Interval, $\underline{F}(4, 480) = 2.03$, $\underline{p} < .025$, were significant for the error data. The former interaction is a function of the error rates being elevated in the prepared conditions for the overlapped placement (7.6%) relative to the adjacent placement (3.0%). The latter interaction is due to error rates for the adjacent placement decreasing from the 375 ms interval onward, whereas for the overlapped placement they did not. No terms involving the display factor were significant in the error analysis.

To summarize, the manipulation of display condition had little effect when it involved alternating locations. However, when the display grouped either the left-right or inner-outer locations by similarity, RTs were faster for all of the precue conditions. The inner-outer grouping also provided an additional benefit for the conditions that involved the inner-outer and alternating locations.

Experiment 2: Altering the Salient Features of the Response Set

Previous results suggest that the hand distinction is used to code the response set when the positioning of the hands makes them more salient (Proctor & Reeve, 1986). Experiment 2 examined the role of hand positioning for a situation in which the stimulus and response sets lack well-defined spatial features. The question addressed in this experiment was whether the hand distinction determines which coding is used.

The arrangements for both stimuli and responses were four spatial locations arranged in square configurations, rather than linearly. The features of the square configurations are less well-defined than those of the linear configurations and can be considered ambiguous. The features that are involved are the four sides and the diagonals. The diagonals seemingly are less salient than the sides and, thus, precuing the diagonal locations should yield the longest RTs. For the sides, spatial proximity does not favor either the left-right distinction or the top-bottom distinction. Because of the spatial ambiguity, the distinction between hands may determine the coding that is used. If the hand distinction determines which of the two ambiguous spatial codings is used, a precuing advantage should be obtained for the prepared:hand condition, regardless of whether the hands are assigned to the left-right or top-bottom sides.

Method. Thirty-two subjects were tested in a single session each. Sixteen used a left-right hand placement, and 16 used a top-bottom placement. For both placements, the fingers were situated on the 1, 3, 7, and 9 keys of the keyboard's numeric pad. The stimulus display and hand placements are shown in Table 4. For the left-right placement, the hands were situated on the left and right sides, whereas for the top-bottom placement, the hands were situated on the top and bottom sides. For subjects using the top-bottom placement, half placed their right hands on the top keys and left hands on the bottom keys, and half did the opposite.

Insert Table 4 about here

Unlike Experiment 1, the warning, precue, and target stimuli were all presented at the same four locations. As a consequence, the presentation procedure had to be modified. The warning stimuli first appeared in all four locations. In the prepared conditions, two of the stimuli then went off, and after a variable precuing interval, only the target was left on the screen. In the unprepared condition, the three nontarget locations went off simultaneously, after a variable interval. This method necessitated that a 125-ms precuing interval be used instead of the 0-ms interval. The remainder of the methods were as described in the General Methods section.

Results. The RTs showed the typical main effects of interval, $F(4, 120) = 60.8$, $p < .001$, and precue, $F(3, 90) = 133.1$, $p < .001$, as well as a Precue x Interval interaction, $F(12, 360) = 2.68$, $p < .01$. Additionally, the Precue x Hand Placement interaction was significant, $F(3, 90) = 6.15$, $p < .001$ (see Table 5). RTs were slower for the precues that corresponded to the diagonal locations (the prepared:finger condition for the top-bottom placement and the prepared:neither condition for the left-right placement) than for the precues that corresponded to the sides, particularly for the top-bottom placement. Moreover, for the latter precues, the hand distinction had little effect. That is, RTs for the prepared:hand condition were approximately equal to those for the conditions involving the sides that did not coincide with the hand distinction (the prepared:neither condition for the top-bottom placement and the prepared:finger condition for the left-right placement).

Insert Table 5 about here

The error data showed only a main effect for precue, $\underline{F}(3, 90) = 3.52$, $\underline{p} < .02$, and an interaction of Interval x Hand Placement, $\underline{F}(4, 120) = 3.12$, $\underline{p} < .02$. The former effect reflects the error rate being greater in the prepared:hand condition (3.0%) than in the other three conditions (unprepared, 1.6%; prepared:finger, 1.8%; prepared:neither, 1.8%). The latter effect is due to the error rate tending to be less at intermediate intervals with the left-right hand placement, but greater at those intervals with the top-bottom placement (see Table 6).

Insert Table 6 about here

To summarize, as has been found for linear stimulus-response arrangements, the square arrangements produce a hierarchy of precuing benefits: Precuing the diagonal locations is less effective than precuing the sides. For the sides, precuing locations that correspond to fingers from the same hand does not produce an additional benefit relative to fingers from different hands. This lack of evidence for hand coding is consistent with results obtained with ambiguous diamond-shaped stimulus and response arrangements (Miller, 1985; Reeve & Proctor, 1985).

Experiment 3: Altering the Salient Features of the Stimulus and Response Sets

Experiment 1 manipulated the characteristics of the stimulus set, whereas Experiment 2 manipulated the characteristics of the response set. In Experiment 3, both the stimulus and response sets were varied orthogonally. An orthogonal manipulation of the two sets allows evaluation of the influence of the correspondence between the features of the stimuli and responses.

The experiment used the spatially ambiguous stimulus and response arrangements from Experiment 2, with the left-right and top-bottom hand placements used in that experiment. However, the stimuli incorporated the "+" and "o" characters used in Experiment 1 to specify spatial locations. The resulting similarity grouping could provide a salient feature for the stimulus sets that was not present in Experiment 2. Experiment 3 used stimulus conditions for which the similarity feature grouped the display into either two rows or two columns, as well as conditions that did not contain a grouping feature. In addition, subjects performed with either the left-right or top-bottom hand placement (see Table 7).

Insert Table 7 about here

<u>Method</u>. Ninety-six subjects were tested, 48 of whom used the left-right hand placement and 48 the top-bottom placement. For each hand placement, 16 subjects were tested with each of the three display conditions: Control; left-right similarity grouping; and top-bottom similarity grouping (see Table 7).

<u>Results</u>. For RTs, the main effects of interval, $\underline{F}(4, 360) = 36.7$, $\underline{p} < .001$, and precue, $\underline{F}(3, 270) = 402.1$, $\underline{p} < .001$, as well as the Precue x Interval interaction , $\underline{F}(12, 504) = 7.44$, $\underline{p} < .001$, were significant. The main effect of hand placement also was significant, $\underline{F}(1, 90) = 12.5$,

$p < .001$, with responses being faster with the left-right placement (M = 539 ms) than with the top-bottom placement (M = 590 ms). A similar difference was evident in Experiment 2, although it was not significant.

Also significant were the interactions of Precue x Hand Placement, $F(3, 270) = 8.87$, $p < .001$, and Precue x Interval x Hand Placement, $F(12, 1080) = 2.18$, $p < .05$. The interaction of Precue x Hand Placement again shows that RTs were slower for the prepared conditions in which the diagonal locations were precued (the prepared:neither condition for the left-right placement and the prepared:finger condition for the top-bottom placement). As in Experiment 2, this difference was most pronounced for the top-bottom placement (see Table 8). No interpretable pattern is apparent for the three-way interaction of precue and hand placement with interval. No terms involving the variable of display condition were significant.

Insert Table 8 about here

For errors, the main effects for hand placement, $F(1, 90) = 7.56$, $p < .01$, interval, $F(4, 360) = 4.71$, $p < .001$, and precue, $F(3, 270) = 7.01$, $p < .001$, were significant. As in Experiment 2, the hand placement effect was due to more errors being made with the top-bottom placement (3.3%) than with the left-right placement (1.6%). As indicated by the other significant effects, the percentage of errors increased with increasing interval (Ms = 1.9%, 1.9%, 2.6%, 2.7%, and 3.2% for the intervals of 125, 375, 750, 1500, and 3000 ms, respectively) and was greater in the prepared conditions (Ms = 3.1%, 2.8%, and 2.3% for the prepared:hand, prepared:finger, and prepared:neither conditions) than in the unprepared condition (M = 1.7%).

Although display condition did not affect RTs significantly, the interactions of Interval x Hand Placement x Display Condition, $F(8, 360) = 2.08$, $p < .05$, and Precue x Interval x Display Condition, $F(24, 1080) = 1.86$, $p < .01$, were significant for the error data. However, no systematic patterns were evident for these interactions. Thus, the primary finding of Experiment 3 is that the manipulation of similarlity grouping had no systematic effect on performance.

Experiment 4: Altering the Spatial Correspondence Between the Stimulus and Response Sets

Reeve and Proctor (1985) compared RTs from two experiments that used horizontal stimulus and response arrangements but that differed in the specific placement of the hands. In one experiment, the hands were placed on adjacent keys in the center of the keyboard, and thus the spatial positioning corresponded closely to that of the display. In the other experiment, the hands were placed at the ends of the keyboard, thus causing the response arrangement to have a large, central gap that was not present in the display. RTs were faster overall in the former experiment than in the latter, suggesting that a direct spatial correspondence minimizes RT.

Experiment 4 provided a more thorough examination of the roles of absolute and relative spatial correspondence. Horizontal stimulus and response arrangements were used. However, the absolute spatial characteristics of the sets were manipulated factorially. Two spatial arrangements, "together" and "separated", were used for both the stimulus set and the response set. The together arrangements had the four locations spaced equally in the center of the stimulus display and response area. The separated arrangements had the two leftmost and two rightmost locations separated by a large gap.

Method. Thirty-two subjects were tested, 16 with the together hand placement and 16 with the separated placement. The stimulus and response arrangements were the horizontal, linear arrangements of the type described in the General Methods and were either equally spaced or separated into two groups by a 10-cm gap between the two center elements. For the together hand placement, the fingers were situated on the **V, B, N, and M** keys, whereas for the separated placement, the fingers were situated on the **Z, X, ., and /** keys. Display type was manipulated within subjects. Half of the subjects were tested with the equally-spaced display in a first session and the separated display in a second session, and vice versa for the other half of the subjects.

Results. For RTs, the effects of interval, $F(4, 120) = 88.2$, $p < .001$, precue, $F(3, 90) = 39.6$, $p < .001$, and Interval x Precue, $F(12, 360) = 5.41$, $p < .001$, were significant. The only other significant term was the Display x Precue interaction, $F(3, 90) = 8.79$, $p < .001$. This interaction reflects the functions shown in Figures 1 and 2. When the display was together, the pattern of RTs was similar to that usually obtained in the precuing studies, and separating the hands added a constant to the RTs (see Figure 1). In contrast, when the display was separated, RTs for the prepared:finger and prepared:neither conditions were elevated relative to the prepared:hand condition. Thus, the two conditions involving precued fingers on different hands were hindered by the separation of the two display halves. The response placement had little effect on the RT patterns.

Insert Figures 1 and 2 about here

For errors, the main effect of precue was significant, $F(3, 90) =$

4.01, $p < .01$ (error rates of 2.2% for the unprepared, prepared:hand, and prepared:finger conditions and 2.7% for the prepared:neither condition), as was the Precue x Interval interaction, $F(12, 360) = 3.84$, $p < .001$. This interaction is a function of the error rates reaching a maximum at a shorter interval for the prepared conditions than for the unprepared condition. Also, the Display x Hand Placement interaction was marginally significant, $F(1, 30) = 3.51$, $p = .07$, and the Display x Precue x Hand Placement, $F(3, 90) = 4.84$, $p < .01$, interaction was significant. These interactions are shown in Table 9. With the exception of the prepared:hand condition, the percentage of errors was greater when the display and hand placements did not correspond.

Insert Table 9 about here

A follow-up experiment, Experiment 4A, was conducted using three types of displays: (1) the together display (++++); (2) the separated display (++ ++); and (3) a partitioned display (+ ++ +), with 16 subjects tested for each display. In this experiment, all subjects performed with the adjacent hand placement. RTs again showed effects of interval, $F(4, 180) = 135.3$, $p < .001$, precue, $F(3, 135) = 26.42$, $p < .001$, and their interaction, $F(12, 540) = 7.42$, $p < .001$. In addition, the interaction of Precue x Display, $F(6, 135) = 6.28$, $p < .001$, was significant. This interaction is shown in Figure 3. The together display produced the typical precuing benefit for the prepared:hand condition, and this benefit was enhanced for the separated display. Thus, the two patterns of RTs from Experiment 4 were replicated. Most importantly, for the partitioned display (+ ++ +), the precuing benefit was greatest for the prepared:finger condition. Thus, the RTs were fastest for the pairs of locations made most salient by the display arrangement.

Insert Figure 3 about here

The error data showed only a significant interaction of Precue x Interval, $F(12, 540) = 3.43$, $p < .001$. As shown in Table 10, this interaction reflects primarily a tendency for the percentage of errors to increase at the longest interval for the unprepared condition but to decrease across intervals for the prepared conditions.

Insert Table 10 about here

Experiment 5: Altering the Orientation Correspondence Between the Stimulus and Response Sets

Experiment 5 examined the nature of coding when the stimulus and response sets both have distinct spatial arrangements but different spatial orientations. In this experiment, the horizontal arrangement (described in the General Methods) and a vertical arrangement (described in Proctor & Reeve, 1986) were used for both stimuli and responses. The experiment involved a complete factorial design, with one factor being the horizontal or vertical arrangement of the stimuli and the other being the horizontal or vertical arrangement of the responses.

When the stimulus and response sets are either both horizontal or both vertical, and an adjacent hand placement is used, the prepared:hand condition shows a precuing advantage. This advantage occurs because the prepared:hand condition corresponds to the left-right or top-bottom distinction (Proctor & Reeve, 1986; Reeve & Proctor, 1984). When the stimulus and response sets combine the vertical and horizontal arrangements, the overall RTs should be slower, because the correspondence between the spatial orientations of the sets is less direct. This finding would be consistent with the outcome regarding the absolute correspondence between the stimulus and response arrangements in Experiment 4.

All combinations of the two stimulus orientations and two response orientations should show a prepared:hand advantage. This advantage is predicted because the prepared:hand condition is consistent with the top-bottom and/or left-right distinction for all of the situations. As was found in Experiment 4, the magnitude of the prepared:hand advantage should depend only on the correspondence of these features and, thus, should be equivalent for all combinations of stimulus and response orientations.

Method. Sixty-four subjects were tested, 16 for each combination of horizontal or vertical displays and horizontal or vertical response arrangements. Adjacent hand placements were used for both response arrangements. For the vertical response orientation, the positioning of the hands was accomplished by having subjects respond on the center column keys of the numeric pad (the **8**, **5**, **2**, and **.** keys), with the hands turned inward (see Proctor & Reeve, 1986). For the vertical stimulus arrangement, the three rows of stimuli were rotated such that they became three columns. The warning stimulus was the left column, the precue stimulus was the center column, and the target stimulus was the right column.

Results. For RTs, the effects for interval, $F(4, 240) = 255.0$, $p < .001$, precue, $F(3, 180) = 34.3$, $p < .001$, and Precue x Interval, $F(12, 720) = 13.4$, $p < .001$, were significant. Additionally, the main effect of response orientation, $F(1, 60) = 5.35$, $p < .025$, and its interactions with precue, $F(3, 180) = 4.60$, $p < .005$, and with display orientation, $F(1, 60) = 17.6$, $p < .001$, were significant. The main effect reflects slower RTs with the vertical response orientation ($M = 678$ ms) than with the horizontal orientation ($M = 614$ ms). The interaction with precue indicates a difference in the ordering of the prepared conditions for the two response orientations. The prepared:neither condition was the slowest with the horizontal response orientation, and the prepared:finger condition was the slowest with the vertical response orientation (see Figure 4). This effect shows the importance of spatial locations, in that the prepared:finger and prepared:neither conditions switch the relative spatial locations to which they are assigned when the orientation is changed (see Proctor & Reeve, 1986). The interaction of response orientation with display orientation indicates that responses were faster when the orientations were the same than when they were different (see Figure 5).

Insert Figures 4 and 5 about here

For errors, the main effects of interval, $F(4, 240) = 11.5$, $p < .001$, and precue, $F(3, 180) = 6.18$, $p < .001$, were significant. The interval effect reflects more errors at the short intervals than at the longer intervals (Ms = 4.8%, 5.6%, 3.5%, 2.8%, and 3.1% for the intervals of 0, 375, 750, 1500, and 3000 ms, respectively), whereas the effect of precue reflects fewer errors being made in the unprepared condition ($M = 2.9\%$) than in the prepared conditions (Ms = 4.6%, 3.9%, and 4.5% for the prepared:hand, prepared:finger, and prepared:neither conditions, respectively). The only significant interaction for errors was that of Precue x Display Orientation x Response Orientation, $F(3, 180) = 3.91$, $p < .01$. This three-way interaction indicates that changing from congruent display and response orientations had different effects on the respective preparation conditions for vertical and horizontal orientations (see Table 11). For horizontal displays, the percentage of errors increased for all except the prepared:neither condition when the response orientation was vertical rather than horizontal. In contrast, for vertical displays, changing from a vertical to a horizontal response orientation decreased the percentage of errors for all conditions except the prepared:finger condition.

Insert Table 11 about here

Summary of Experiments 1-5

Several basic points emerge from Experiments 1-5. Manipulations of similarity grouping for the stimulus displays affect performance in some conditions but not in others. With the linear displays used in Experiment 1, when similarity grouping was consistent with either the left-right or inner-outer location distinctions, performance was improved overall. In addition, similarity grouping for the less salient inner-outer distinction produced relatively greater precuing benefits for the conditions assigned to the inner-outer and alternating locations. However, when similarity grouping was consistent with the alternating locations (Experiment 1) or with the sides of a square display arrangement (Experiment 3), little effect on RTs was apparent.

With the square stimulus and response arrangements (Experiments 2 and 3), coding based on the hand distinction was not evident. Precuing a side that involved fingers from each hand was approximately as beneficial as precuing a side that involved fingers from a single hand. Precuing either of the side conditions was more effective than precuing the diagonal condition, particularly for the top-bottom hand placement. Thus, as with the linear arrangements, the precuing benefits are not equivalent for all pairs of locations.

When incongruencies in orientation of the stimulus and response sets that do not involve altering the relative locations are introduced (Experiment 5), only a constant is added to RTs. However, when the relative spacing of locations is manipulated within the sets (Experiments 4 and 4A), the pattern of precuing benefits is affected. This effect is primarily a function of the relative spacing of the stimuli and not of the responses. Thus, Experiments 1-5 collectively indicate that the properties of the stimulus set are more important than the properties of the response set in determining the nature of the codings that are employed in various tasks.

Retention and Transfer of the Benefits of Practice

Studies of practice effects on skilled performance suggest that practice with a consistent assignment of stimuli and responses should improve performance, even for assignments that initially are of low compatibility (Eberts, 1984; Schneider & Fisk, 1983). However, the few studies that have examined practice effects on S-R compatibility have produced mixed results. For some situations, compatibility effects have been found to change little with practice (Fitts & Seeger, 1953; Garvey & Knowles, 1954; Gopher, Karis, & Koenig, 1985), whereas for others, practice has been shown to eliminate the difference between compatible and incompatible conditions (Schneider & Fisk, 1983).

In our initial research investigating practice effects (Proctor & Reeve, 1988), subjects were tested in the basic spatial-precuing task for three sessions, using either the adjacent or overlapped hand placement for all sessions. For both hand placements, the initial pattern of differential precuing benefits for the prepared conditions was eliminated by the third session. In that session, all of the prepared conditions showed substantial precuing benefits relative to the unprepared condition. Subsequent experiments used transfer designs in which new assignments of fingers to response locations were introduced in a fourth session. The results indicated that task-specific procedures develop between stimuli and fingers that do not transfer to a new finger assignment.

The retention and transfer of the benefits that occur with practice is a relatively neglected issue in the S-R compatibility literature. The lack of research on these topics limits understanding of S-R compatibility, because performance under conditions of retention and transfer provides an important indicator of what is acquired with practice (Schmidt, 1988). The experiments described in this section provide information about the changes in the coding of stimulus and response features that occur as a function of practice, retention, and transfer.

Experiment 6: Retention Effects with Spatial Arrangements

Experiment 6 examined the retention of the task-specific procedures that are acquired with practice. The experiment used horizontal stimulus and response arrangements, with the adjacent hand placement (Reeve & Proctor, 1984). Subjects had three consecutive days of practice. Following the initial practice, half of the subjects returned for a fourth consecutive session; the other half returned following a one-week retention interval. The retention test was used to determine whether the changes that occur with practice, which result in the elimination of the pattern of differential precuing benefits (Proctor &

Reeve, 1988), are retained for a week.

Method. Thirty-two subjects were tested for four sessions. The General Methods described earlier were used, with the horizontal stimulus display and the horizontal, adjacent response arrangement. For all subjects, the first three sessions were on consecutive days. Half of the subjects received their fourth sessions on the following day, whereas the other half received them a week later.

Results. RTs for sessions 1-3 showed effects of interval, $F(4, 120) = 110.3$, $p < .001$, precue, $F(3, 90) = 44.9$, $p < .001$, and Precue x Interval, $F(12, 360) = 20.3$, $p < .001$. A main effect for session, $F(2, 60) = 18.1$, $p < .001$, indicated that RTs became faster with practice (Ms = 523, 480, and 468 ms for sessions 1, 2, and 3, respectively). Also, interactions of session with precue (see Table 12), $F(6, 180) = 9.00$, $p < .001$, and with interval, $F(8, 240) = 18.5$, $p < .001$, were significant. The pattern of differential precuing benefits for the three prepared conditions was obtained in session 1, but by the third session, little difference existed. Similarly, the interval functions flattened across sessions, because RTs at short intervals were reduced by practice more than were those at long intervals. The entire pattern of results for sessions 1-3 replicated the findings of Proctor and Reeve (1988).

Insert Table 12 about here

The error data for sessions 1-3 showed a main effect of session, $F(2, 60) = 9.76$, $p < .001$, a Session x Precue interaction, $F(6, 180) = 3.86$, $p < .01$, and a Precue x Interval interaction, $F(12, 360) = 3.20$, $p < .001$. The percentage of errors decreased across sessions (session 1, 2.7%; session 2, 2.0%, and session 3, 1.6%). The decrease was due entirely to the prepared conditions, with the percentage of errors for the unprepared condition increasing slightly. The interaction of precue with interval was due to the percentage of errors for the prepared conditions decreasing across intervals, whereas that for the unprepared condition increased.

For session 4 the RTs again showed main effects of precue, $F(3, 90) = 33.9$, $p < .001$, and interval, $F(4, 120) = 54.4$, $p < .001$, as well as their interaction, $F(12, 360) = 8.39$, $p < .001$. The error data showed a main effect of interval, $F(4, 120) = 3.62$, $p < .01$, and an interaction of interval with precue, $F(12, 360) = 3.28$, $p < .001$. Most importantly, none of the terms involving the retention factor (immediate versus delayed) were significant for either the RTs (see Table 13) or errors. Both the immediate and delayed retention tests showed only small differences between the RTs for the three prepared conditions, indicating that the changes produced by practice were retained for at least a week.

Insert Table 13 about here

Experiment 7: Extended Practice and Transfer with Spatial Arrangements

In our practice study (Proctor & Reeve, 1988), transfer effects were evaluated for situations in which subjects performed the precuing task with the adjacent or overlapped hand placement, following practice with the other placement. When switched from the overlapped placement to the adjacent placement, the pattern of differential precuing benefits was reinstated completely. A similar, but nonsignificant, tendency was apparent when the switch was from the adjacent placement to the overlapped placement. Control experiments suggested that even for this situation, translative coding operations again were used in the transfer session.

One limiting factor regarding the results of this study is that only relatively short-term practice was involved. Although this amount of initial practice was sufficient to eliminate the pattern of differential precuing benefits, it may not have been sufficient to develop procedures that would generalize to a different hand placement. That is, the effects of transfer are known to change as a function of the amount of initial practice (Fitts & Posner, 1967; Schmidt, 1988).

Experiment 7, therefore, examined the effect of extended practice with the spatial-precuing task. Subjects practiced for 12 sessions with the horizontal stimulus and response arrangements, using the overlapped hand placement. Then, they were transferred to the adjacent placement and tested for four more sessions. The extended practice should be sufficient for positive transfer to occur from one hand placement to the other, if such transfer is possible.

Method. Fourteen subjects were tested for 16 sessions each, four sessions per week. For the first 12 sessions, each subject performed with the overlapped hand placement. For the last four sessions, all subjects were transferred to the adjacent placement. The direction of transfer was from the overlapped to the adjacent placement, because in our previous study of shorter duration practice, this direction produced complete reinstatement of the pattern of differential precuing benefits (Proctor & Reeve, 1988). In all other respects, the method was as specified in the General Methods.

Results. To evaluate the effect of practice, the data for the first and last practice sessions with the overlapped hand placement were analyzed. The RTs showed the usual effects of precue, $F(3, 39) = 21.9$,

$p < .001$, interval, $F(4, 52) = 56.7$, $p < .001$, and their interaction, $F(12, 156) = 3.80$, $p < .001$. In addition, the main effect of session, $F(1, 13) = 63.3$, $p < .001$, the Session x Interval interaction, $F(4, 52) = 9.76$, $p < .001$, and the Session x Precue interaction, $F(3, 39) = 5.22$, $p < .005$, were significant. Responses were faster in session 12 (M = 470 ms) than in session 1 (M = 619 ms), and RTs decreased less with interval in the twelfth session than in the first. More importantly, the typical pattern of differential precuing benefits was apparent in session 1 but not in session 12 (see Table 14). The error data also showed a main effect of session, $F(1, 13) = 12.4$, $p < .005$, as well as interactions of Precue x Interval, $F(12, 156) = 2.24$, $p < .02$, and Precue x Interval x Session, $F(12, 156) = 2.22$, $p < .02$.

Insert Table 14 about here

For the transfer week (sessions 13-16), the error data showed no significant effects. For RTs, the standard effects of precue, $F(3, 39) = 42.0$, $p < .001$, interval, $F(4, 52) = 67.5$, $p < .001$, and Precue x Interval, $F(12, 156) = 8.33$, $p < .001$, were significant. The only other significant effect was that of session, $F(3, 39) = 7.13$, $p < .001$. As can be seen in Table 14, RTs decreased across the sessions. Also evident in Table 14 is that the precue effect was due almost entirely to the unprepared condition being slower than the prepared conditions. In sessions 13-16, only relatively small differences between the prepared:hand and prepared:neither conditions were obtained.

Experiment 8: Transfer Between Spatial Arrangements

Experiment 8 evaluated the nature of transfer between spatially-arranged stimulus and response sets, rather than between hand placements. Using the adjacent hand placement, subjects in Experiment 8 practiced for three sessions with one of three arrangements of stimulus and response sets, and then were transferred to a common set. The three arrangements were (a) the horizontal stimulus and response sets (the horizontal arrangement), (b) the vertical stimulus and response sets (the vertical arrangement), and (c) the vertical stimulus set with a vertical, adjacent-side placement (the vertical-side arrangement; see Proctor & Reeve, 1986). On the fourth session, all subjects were tested with the vertical-side arrangement. If positive transfer occurs (i.e., if no differences between the respective precued conditions are present in the transfer session), the transfer will indicate that the task-specific procedures acquired with practice are independent of orientation.

Method. Thirty-nine subjects were tested. All subjects received three practice sessions, followed by a transfer session. A third of the subjects practiced with the horizontal arrangement; another third practiced with the vertical arrangement; and a final third practiced with the vertical-side arrangement. For this latter arrangement, the subject's hands were placed to the right, on keys that were aligned with the vertically displayed stimulus set (see Proctor & Reeve, 1986). In the transfer session, all subjects were tested with the vertical-side arrangement.

Results. The RT data for sessions 1-3 showed main effects of session, $F(2, 72) = 7.48$, $p < .001$, and arrangement, $F(2, 36) = 6.32$, $p < .005$. Responses became faster with practice (Ms = 587, 520, and 505 ms for sessions 1, 2, and 3, respectively) and were faster with the horizontal arrangement (M = 464 ms) than with either the vertical (M = 590 ms) or vertical-side (M = 563 ms) arrangements. As in the other experiments, the main effects of precue, $F(3, 108) = 54.2$, $p < .001$, and interval, $F(4, 144) = 177.6$, $p < .001$, as well as their interaction, $F(12, 432) = 35.9$, $p < .001$, were significant. Responses were slower overall for the unprepared condition ($M = 562$ ms) than for the prepared conditions, which showed the usual pattern of differential precuing benefits (Ms = 513, 525, and 549 ms for the prepared:hand, prepared:finger, and prepared:neither conditions, respectively). RTs also decreased across intervals, particularly for the prepared conditions.

Finally, interval and precue entered into three-way interactions with session, $F(24, 864) = 2.07$, $p < .005$, and with arrangement, $F(24, 432) = 1.85$, $p < .01$. The decrease of RT with interval for the prepared conditions, relative to the unprepared condition, was less with the horizontal arrangement than with the vertical and vertical-side arrangements, and was less at later sessions than at earlier sessions. Interval alone also interacted with session and arrangement, $F(16, 288) = 2.06$, $p < .01$. This interaction reflects the difference in interval functions for the three arrangements becoming less pronounced with practice.

The error data for sessions 1-3 showed a main effect of session, $F(2, 72) = 7.57$, $p < .001$, and interactions of session with arrangement, $F(4, 72) = 3.37$, $p < .02$, and precue, $F(6, 216) = 3.28$, $p < .01$. The main effect of interval also was significant, $F(4, 144) = 7.63$, $p < .001$, as were the interactions of interval with arrangement, $F(8, 144) = 2.44$, $p < .02$, and precue, $F(12, 432) = 3.87$, $p < .001$.

In the fourth session, the effects of precue, $F(3, 108) = 27.1$, $p < .001$, interval, $F(4, 144) = 109.9$, $p < .001$, and Precue x Interval, $F(12, 432) = 13.6$, $p < .001$, for RTs again were significant.

Additionally, the main effect of arrangement, $F(2, 36) = 3.29$, $p < .05$, and the interactions of Precue x Arrangement, $F(6, 108) = 2.56$, $p < .025$, and Interval x Arrangement, $F(8, 144) = 2.41$, $p < .025$, were significant. Subjects who practiced with the vertical-side arrangement ($M = 511$ ms) were faster than those who practiced with the horizontal ($M = 591$ ms) or vertical ($M = 585$ ms) arrangements. The Precue x Arrangement interaction indicates that for the subjects who practiced with the horizontal and vertical arrangements, the pattern of differential precuing benefits (the prepared:hand advantage) was reinstated in the fourth session (see Table 15). Subjects who had practiced with the vertical-side arrangement did not show the prepared:hand advantage, but a slight, nonsignificant advantage for the prepared:finger condition, instead. Similarly, the effect of interval was considerably less for subjects who had practiced with the vertical-side arrangement than for subjects who had practiced with either the horizontal or vertical arrangement.

Insert Table 15 about here

The error data for session 4 showed only main effects of interval, $F(4, 144) = 5.51$, $p < .001$, and arrangement, $F(2, 36) = 4.02$, $p < .03$. In sum, little if any transfer was evident for subjects who changed arrangements, indicating that the procedures acquired with practice are specific to the initial task.

Because of the lack of transfer in Experiment 8, a follow-up experiment (Experiment 8A) was conducted, in which 32 subjects practiced for three sessions using either the horizontal or vertical stimulus display, but with the horizontal, adjacent hand placement (this procedure is similar to that of Experiment 5). In the fourth session, all subjects performed with the horizontal display and the horizontal, adjacent response placement. The purpose of Experiment 8A was to determine whether transfer would occur if only the orientation of the stimulus set was changed.

The typical results were obtained for the practice sessions. Of most importance, the only significant term involving display orientation for either RTs or errors was the main effect for RTs, $F(1, 30) = 10.1$, $p < .001$. Responses were faster with the horizontal display ($M = 520$ ms) than with the vertical display ($M = 626$ ms), thus replicating the results of Experiment 5.

In the fourth session, the RTs showed only effects of precue, $F(3, 90) = 18.0$, $p < .001$, interval, $F(4, 120) = 65.8$, $p < .001$, and their interaction, $F(12, 360) = 7.65$, $p < .001$, and the errors showed main effects of precue, $F(3, 90) = 3.91$, $p < .02$, and interval, $F(4, 120) = 4.52$, $p < .01$. Most importantly, no terms involving the display orientation with which the subjects had practiced approached significance for either RTs or errors. As is shown in Table 16, RTs for subjects who had practiced with the vertical display were virtually identical to those for subjects who had practiced with the horizontal display. Only a slight difference between the three prepared conditions existed, which is typical for practiced subjects.

Insert Table 16 about here

Experiment 9: Practice and Retention Effects with Symbolic Stimuli

Experiment 9 used two-dimensional, symbolic stimuli from the set, **O, o, z,** and Z, used previously by Proctor and Reeve (1985). For this set, the dimensions of letter identity and size specify the responses.

Proctor and Reeve examined two assignments of the stimuli to keypress responses. For the OozZ assignment, the stimuli O, o, z, and Z were assigned to the left-middle, left-index, right-index, and right-middle fingers, respectively. For the OzoZ assignment, the left-to-right assignment was O, z, o, and Z. Letter identity, which is the salient feature of this stimulus set, distinguishes between the salient left and right response locations (and hands) with the OozZ assignment but not with the OzoZ assignment. In Proctor and Reeve's experiments, the former assignment produced faster RTs than did the latter, indicating that performance is better when the salient features of the stimulus and response sets correspond than when they do not.

Experiment 9 addressed several issues. First, two new assignments, the oOzZ and ozOZ assignments, were used. With the OozZ and OzoZ assignments used previously, the size feature distinguishes between index-finger and middle-finger responses (the inner and outer locations) for both assignments. The assignments differ in whether the left-hand and right-hand responses (the two leftmost and two rightmost response locations) are distinguished by letter identity. The new oOzZ and ozOZ assignments also differ in whether letter identity distinguishes the left-hand and right-hand responses, but size does not distinguish the index- and middle-finger responses. Thus, relative to the original assignments, the new assignments allow evaluation of not only the role of the salient features but also of the secondary size and inner-outer features.

A second issue of interest in Experiment 9 was whether the symbolic-compatibility effect (i.e., the difference in RTs for the OozZ and OzoZ assignments) disappears with practice, as does the pattern of differential precuing benefits in the spatial-precuing task. A third issue was that if the symbolic-compatibility effect is eliminated with practice, does its elimination follow a time course similar to that of the spatial-compatibility effect? A fourth issue was whether the effects of practice are retained across a one-week interval, as they are in the spatial-precuing task.

Method. Sixty-four subjects were tested for four sessions each. The first three sessions were on consecutive days, and the fourth session was conducted after a one-week retention interval. Each subject used one of four assignments of stimuli to responses in all four sessions. The assignments were oOzZ, ozOZ, OozZ, and OzoZ, with the left-to-right ordering of letters indicating their order of assignment to the V, B, N, and M keys, respectively.

Results. Analysis of the RT data for sessions 1-3 showed a main effect of session, $F(2, 120) = 53.2$, $p < .001$. The assignment main effect was not significant, $F < 1.0$, but the interaction of assignment with session was, $F(6, 120) = 4.28$, $p < .001$. As shown in Figure 6, the usual differences between the OozZ and OzoZ assignments was replicated in session 1. Also, the new oOzZ and ozOZ assignments showed similar RTs that were slightly slower than those for the OozZ assignment. The lack of difference between the two new assignments indicates that a relation between the secondary size feature of the stimulus set and the salient left-right spatial feature of the response set is as effective as is a relation between the salient letter-identity feature and the salient left-right feature. Moreover, the fact that the new ozOZ yields faster RTs than the old OzoZ assignment indicates that the relation of size to the left-right feature is more beneficial than is the relation of size to the secondary inner-outer feature of the response set. The differences apparent between the four assignments in session 1 are largely eliminated by the third session. The error data showed only a main effect of session, $F(2, 120) = 17.4$, $p < .001$.

Insert Figure 6 about here

Retention was evaluated by comparing session 3 to session 4, which occurred a week later. Neither the main effect of session nor its interaction with assignment was significant for either the RTs (see Figure 6) or the errors, $Fs < 2.1$, $ps > .10$. Thus, as with the spatial-precuing task, practice on the symbolic-compatibility task produces rapid changes that are relatively durable.

Experiment 10: Transfer Between Symbolic and Spatial Stimuli

Experiment 10 examined the effects of being transferred to the spatial-location stimulus set after practice with the symbolic stimulus set. The logic was to determine whether emphases on particular response locations with one stimulus set have effects on how subjects code the responses with the new stimulus set. The experiment involved training one group of subjects with the OozZ assignment of symbolic stimuli and another group with the OzoZ assignment. All subjects then were transferred to the horizontal spatial-location stimuli. For the OozZ assignment, the salient letter-identity feature is consistent with the left-right distinction for the response set. Thus, subjects trained with the OozZ assignment should show the usual pattern of differential precuing benefits, when switched to the spatial-location precuing task. In contrast, for the OzoZ assignment, letter identity is consistent with alternating locations. If the alternating locations become more salient with practice because of this relation, then the pattern of differential precuing benefits either should be diminished or should not be apparent for the subjects trained with the OzoZ assignment.

Method. Twenty-four subjects were tested for nine sessions each. For the first eight sessions, half of the subjects performed with the OozZ assignment and half with the OzoZ assignment. In the ninth session, all subjects were transferred to the basic spatial-precuing task.

Results. The RT data for the practice sessions showed main effects of assignment, $F(1, 22) = 7.95$, $p < .01$, and session, $F(7, 154) = 24.5$, $p < .001$, as well as an Assignment x Session interaction, $F(7, 154) = 2.05$, $p = .05$ (see Table 17). Responses were slower with the OzoZ assignment ($M = 617$ ms) than with the OozZ assignment ($M = 547$ ms) and became faster with practice (primarily across sessions 1-4). The advantage for the OozZ assignment decreased from 116 ms in session 1 to 61 ms in session 8. Thus, although the RTs for the two assignments did not converge completely across sessions, as was the case in Experiment 9, the advantage for the OozZ assignment decreased by 55 ms. The error data showed only a marginally significant effect of assignment, $F(1, 23) = 3.62$, $p < .06$.

Insert Table 17 about here

For the transfer session, no terms involving the assignment factor were significant for either the RT or error data, Fs < 1.76, $p > .10$. Regardless of whether subjects practiced with the OozZ or OzoZ assignment, the typical effects on RTs of precue, $F(3, 66) = 15.9$, $p < .001$, interval, $F(4, 88) = 74.7$, $p < .001$, and Precue x Interval, $F(12, 264) = 8.78$, $p < .001$, were obtained. As shown in Table 18, the differences between the three prepared conditions were somewhat smaller than usually occurs, but the pattern is similar for both groups of subjects. Thus, any reduction in the magnitude of the differences between the prepared conditions is independent of the specific assignment of the symbolic stimuli that was used for practice. For errors, only the effect of interval was significant, $F(4, 88) = 5.21$, $p < .001$.

Insert Table 18 about here

Experiment 11: Transfer Between Spatial and Symbolic Stimuli

Experiment 11 involved practicing subjects in the spatial-precuing task, but only with subsets of the precuing conditions, and then transferring the subjects to the symbolic-compatibility task. For one group, the practice was with the prepared:hand condition, whereas for another group, it was with the prepared:neither condition. Each group of subjects was split into two conditions for the transfer session. Subjects in one condition were tested with the OozZ assignment, whereas subjects in the other condition were tested with the OzoZ assignment. An interaction between practice condition and transfer condition was predicted. Subjects who practiced with the prepared:hand condition should show the usual advantage for the OozZ assignment, because for this assignment letter-identity corresponds with the left-right spatial distinction that was precued in practice. In contrast, subjects who practiced with the prepared:neither condition should show less of an advantage for the OozZ assignment, because for this assignment letter identity does not correspond with the alternating locations that were precued, whereas for the OzoZ assignment it does.

Method. Forty-eight subjects were tested. All subjects first performed the spatial-precuing task, with the horizontal stimulus set and the adjacent hand placement. The primary modification from the General Methods was that each subject received precue stimuli from only one condition. Half of the subjects received just the prepared:hand condition, for which the two leftmost or rightmost locations are cued; the other half received just the prepared:neither condition, for which either pair of alternate locations is cued. Following the spatial-precuing task, the subjects performed the symbolic-compatibility task. Half of the subjects for each of the precuing groups were tested with the OozZ assignment of stimuli to responses, whereas half were tested with the OzoZ assignment.

Results. For the initial spatial-precuing task, the finding of most importance was a significant effect of precue condition, $F(1, 44) = 40.2$, $p < .001$. Responses were faster for subjects who received the prepared:hand condition ($M = 424$ ms) than for subjects who received the prepared:neither condition ($M = 508$ ms). A similar difference was evident for the errors, $F(1, 44) = 14.0$, $p < .001$, with fewer errors being made for the prepared:hand condition (1.6%) than for the prepared:neither condition (3.3%).

For the transfer task, there was no main effect on RTs for the type of precue condition that had been received in the practice task, $F < 1.0$. However, both the main effect of assignment, $F(1, 44) = 4.61$, $p < .04$, and the interaction of Assignment x Precue Condition, $F(1, 44) = 6.82$, $p < .02$, were significant. As is customarily found, responses were slower overall with the OzoZ assignment ($M = 663$ ms) than with the OozZ assignment ($M = 623$ ms). But this advantage for the OozZ assignment was apparent only for subjects who had practiced with the prepared:hand condition in the spatial-precuing task (OozZ, $M = 602$ ms;

OzoZ, $\underline{M}$ = 691 ms). For subjects who had practiced with the prepared:neither condition, there was a slight tendency for the OozZ assignment to be slower than the OzoZ assignment (OozZ, $\underline{M}$ = 644 ms; OzoZ, $\underline{M}$ = 636 ms). The error data showed no significant effects. Thus, practice with the alternate-location precues apparently enabled subjects to use the relation between these locations and the salient letter-identity feature to code the stimuli to responses.

Summary of Experiments 6-11

Experiments 6-11 confirm the practice effects established previously for the spatial-precuing task (Proctor & Reeve, 1988). For that task, the pattern of differential precuing benefits that is apparent in the first session is virtually eliminated by the third session (Experiments 6 and 8). For the symbolic-compatibility task, a similar rapid reduction of the initial differences between assignments occurs (Experiments 9 and 10), although it is unclear whether convergence is complete. Thus, for both tasks, differential RT patterns tend to disappear with relatively little practice. Not only do the differential patterns disappear with practice, but these benefits of practice are retained for at least one week in both the spatial-precuing task (Experiment 6) and the symbolic-compatibility task (Experiment 9).

Two consistent results emerge from examining transfer after relatively few practice sessions. First, in situations for which the response set is changed, little transfer occurs. Previously, we found little transfer when the change was from the overlapped to the adjacent hand placement, or vice versa, and from the adjacent to a crossed-hands placement (Proctor & Reeve, 1988). Experiment 8 showed little transfer when the hand placement was changed from either the horizontal or vertical arrangement to the vertical-side arrangement. This lack of transfer occurred despite the fact that the change in hand placement from horizontal to vertical-side maintains the relative finger positions, whereas the change from vertical to vertical-side maintains the orientations of the stimulus and response sets.

In contrast, when the response set is not altered, transfer occurs. Complete transfer was apparent when the orientation of the stimulus set was changed, but the response set was held constant (Experiment 8A). Similarly, when subjects practiced with a subset of the spatial precues that was consistent with the salient letter-identity feature of a subsequent assignment of the symbolic stimuli, a substantial benefit was apparent (Experiment 11).

With extended practice, more generalizable benefits seem to emerge. First, some transfer occurs even when the response set is altered. With the spatial-precuing task, transfer to the adjacent hand placement after 12 sessions of practice with the overlapped placement yielded smaller differences between the three prepared conditions than is customarily obtained (Experiment 7). Second, after eight sessions of practice with the symbolic-compatibility task, subjects transferred to the spatial-precuing task showed a similarly reduced pattern of differential precuing benefits, regardless of the specific assignment they had practiced initially (Experiment 10).

IV. S-R Compatibility: A Salient Features Account

In this section, we present an account of S-R compatibility effects that is based on our empirical research program and is consistent with our review of the compatibility literature. This account centers on the concept of mental representations that are based on salient features of the stimulus and response sets. The evolution of this account has occurred in three phases, which are summarized below.

Phase 1: Development of the Salient Features Coding Principle

The initial research that laid the foundation for the current theoretical perspective was reported in Reeve and Proctor (1984). Three experiments were conducted using variations of the spatial-precuing task. The experiments showed that the pattern of differential precuing benefits (i.e., a same-hand advantage, when hands are adjacent) obtained for that task is a function of spatially-based translation processes. The most important findings were that (a) with a sufficiently long precuing interval of 3 s, all pairs of precued responses showed equivalent benefits, and (b) when the overlapped hand placement was used, the advantage remained with the left-right spatial distinction rather than with the hand distinction. Thus, the findings implicated spatial codings used to translate between precued stimulus and response sets as the source of the differential precuing benefits.

Subsequently, in Proctor and Reeve (1986), we reported additional evidence for spatial coding, using the vertical stimulus displays and response placements rather than the horizontal arrangements. The vertical arrangements showed a top-bottom advantage similar to the left-right advantage found with the horizontal arrangements. Additionally, evidence was found for the use of hand coding (i.e., coding based on the distinction between the two hands) in certain circumstances. Specifically, for the adjacent-hand placement with the vertical arrangement, an enhanced precuing benefit was obtained for the prepared:hand condition. This enhanced benefit was due to an increase in the distinctiveness of the hands caused by the need to turn them inward with the vertical arrangement. This increased distinctiveness was a factor only when it coincided with the salient top-bottom spatial feature.

The consistent orderings of RTs for the precue conditions with linear arrangements, regardless of orientation, indicated a hierarchy of coding based on relative spatial position. The most salient feature is the distinction between the two locations to one side of center and the two locations to the other side. The distinction between the two inner and two outer locations is of intermediate salience, and the pairs of alternating locations are least salient. This hierarchy of salience underlies the pattern of differential precuing benefits.

The importance of spatial coding of the response sets also is indicated by experiments that used two-dimensional, symbolic stimuli (Proctor & Reeve, 1985). For stimuli composed from combinations of two consonants (B, M) and two vowels (E, O), assigned to responses in the left-to-right order of BE, BO, ME, and MO, a same-hand advantage was obtained with a normal, adjacent hand placement. That is, precuing with a consonant produced faster RTs than did precuing with a vowel. However, as with the spatial-precuing task, a similar advantage for the consonant precues was obtained even when the hands were overlapped. Similarly, for the set of stimuli composed from two letter-identities (O, Z) of two sizes (small, large), when used with the adjacent placement or with a placement for which the four responses were on the same hand, RTs were fastest when the more salient letter-identity feature distinguished the two leftmost and two rightmost responses than when it did not.

An exception to this latter finding occurred when the hands were overlapped, such that the fingers from the two hands were alternated. For this hand placement, RTs were equally fast regardless of whether letter identity distinguished between the left and right locations or alternating locations. Because this result only occurred with the overlapped placement, it indicates that when the salient letter-identity feature of the stimulus set is inconsistent with the salient left-right feature of the response set but consistent with the hand distinction, hand coding is used.

The findings from these studies and others (e.g., Reeve & Proctor, 1985) led to the formulation of the **salient features coding principle**:

> Stimulus and response sets are coded in terms of the salient features of each, with response determination occurring most rapidly when the salient features of the respective sets correspond.

Phase 2: The Role of Salient Features in Skilled Performance

The salient-features coding principle was formulated to explain results from single-session experiments. Because theories of skill acquisition postulate distinct stages in which the nature of coding changes and the role of translation processes diminishes with practice (e.g., Anderson, 1987; Fitts & Posner, 1967; Teichner & Krebs, 1974), the next step was to examine performance in multi-session experiments. Additionally, transfer conditions were studied (Proctor & Reeve, 1988). The pattern of differential precuing benefits was eliminated quickly by practice with the spatial-precuing task, regardless of whether an adjacent or overlapped hand placement was used. In the third of three sessions, all pairs of precued responses showed approximately equal precuing benefits. Subsequent experiments showed that the pattern was reinstated fully when subjects transferred in a fourth session from the overlapped placement to the adjacent placement or from the adjacent placement to a placement in which the hands were crossed completely. The pattern was only partially reinstated when transfer was from the adjacent placement to the overlapped placement, but evidence suggested that the lack of complete reinstatement was due to the additional use of hand coding in the transfer session.

A good framework for interpreting the results of the practice and transfer experiments is provided by Anderson's (1982, 1983, 1987) production-system model of skill acquisition. This model distinguishes between general procedures that are used to perform a novel task and task-specific procedures that are acquired with practice. The general procedures rely on declarative representations of the task, which are retained in working memory. In terms of the model, the salient-features coding principle applies to the declarative representations that are used initially to perfom the task. That is, the subject's representations of the task are derived from those features of the stimulus and response sets that are most salient. The elimination of the pattern of differential precuing benefits with practice reflects the development of task-specific procedures that no longer require the declarative representations.

Within this framework, the transfer experiments can be interpreted as follows. The initial declarative representations are based on the salient spatial features of the precuing task. As subjects become practiced and these representations no longer are needed to mediate between stimuli and responses, task-specific procedures are acquired that directly activate finger responses when the appropriate stimuli are presented. When the hand placement is altered, so that the fingers are assigned to different relative locations, the task-specific procedures no longer apply, and subjects revert to using declarative representations. In the case of subjects who transfer from the adjacent to the overlapped hand placement, the pattern of differential precuing benefits is not reinstated completely because hand coding, as well as spatial coding, is used in the subsequent representations. Specifically, the distinction between hands is increased in salience for subjects who practiced with the adjacent placement, because it corresponded with the salient left-right spatial feature. Thus, when transferred to the overlapped placement, for which the hand distinction now is assigned to the alternating locations, subjects have an additional coding feature to aid in translating between stimuli and responses.

Phase 3: Implications of the Empirical Research

The empirical research summarized in this report builds on the account described to this point. Specifically, the research clarifies the role of salient-features coding in the declarative stage of skill acquisition and provides insight into the nature of practice, retention, and transfer effects.

Salient-Feature Coding Operations

Our previous research provided evidence for salient-features coding in the spatial-precuing and symbolic-compatibility tasks primarily through manipulations of stimulus-response assignments and of response-finger to response-location assignments. The present experiments involved direct manipulations of saliency to examine the characteristics of salient-feature coding operations.

Experiments 1-5 demonstrate that manipulations of the relative saliency of the features of stimulus and response sets can influence performance. Moreover, the most influential manipulations involve the stimulus set, rather than the response set. Similarity grouping of stimulus locations was shown to influence the coding of linear arrays (Experiment 1). Additionally, when spatial grouping of both the stimulus and response arrangements was manipulated orthogonally, the stimulus grouping was important in determining the pattern of relative precuing benefits, but the response grouping was not (Experiment 4). Thus, the properties of the stimulus set are the primary determinants of the codings that are used.

The conclusion that the stimulus set is of primary importance is consistent with the results of the studies that have used symbolic stimuli (Proctor & Reeve, 1985). In those experiments, coding of the response set in terms of the hand distinction occurred only when this distinction corresponded with the salient feature of the stimulus set. Similarly, in the spatial-precuing task, evidence for hand coding has been obtained when the distinction between hands is consistent with the salient spatial feature (Proctor & Reeve, 1986). Moreover, hand coding has been implicated in transfer sessions following practice with a situation in which the hand distinction is consistent with the salient spatial feature (Proctor & Reeve, 1988). Although the stimulus and response features were perfectly correlated in these spatial-precuing experiments, the relation of the hand distinction to the stimulus features likely is of most importance.

Within stimulus features, hierarchies exist regarding the relative saliency. In the basic spatial-precuing task, a hierarchy is apparent in the ordering of precuing benefits for precued pairs of left-right (or top-bottom), inner-outer, and alternating locations. With the square arrangements (Experiments 2 and 3), precuing sides similarly produces faster responding than does precuing diagonals. These hierarchies of saliency exist for situations in which the stimulus locations are mapped directly to response locations. Thus, differences in RT occur even within "compatible" stimulus-response assignments.

The importance of the coding hierarchies is apparent in the manipulation of similarity grouping in Experiment 1. Similarity grouping had no effect when it was consistent with the least obvious spatial feature, the alternating locations. However, when the similarity grouping was consistent with the more salient left-right and inner-outer distinctions, a benefit was apparent. Moreover, for the inner-outer distinction, the consistent similarity grouping was effective at enhancing the performance not only for those locations, but also for the alternating locations.

A stronger grouping effect for the stimulus set in the spatial-precuing task is found for spatial manipulations. Separating the two leftmost and two rightmost locations by a gap increases the advantage for precuing those locations and also eliminates the difference between precuing the inner or outer locations versus either pair of alternating locations (Experiments 4 and 4A). Additionally, when the stimulus set is grouped to emphasize the inner-outer locations, the precuing advantage now is found for those locations, rather than for the left-right locations (Experiment 4A).

Finally, similar coding based on spatial features occurs regardless of whether the orientations of the stimulus and response sets correspond (Experiments 5 and 8A). Specifically, having a vertical stimulus set paired with a horizontal response set, or vice versa, adds a constant to the RTs but does not influence the pattern of differential precuing benefits. Thus, the translation processes that produce the pattern of benefits are independent of the processes that produce transformations of orientation.

Practice, Retention, and Transfer

The practice effects in the present study confirm the shift from translation processes, which are based on declarative representations, to task-specific procedures. That is, the initial differences in precuing benefits for the spatial-precuing task (Experiment 6) and assignments for the symbolic-compatibility task (Experiment 9) are largely eliminated by the third session of practice. The retention tests show that the acquired task-specific procedures are relatively durable. When subjects were tested a week after the third session, little decrement in performance was apparent for either the spatial-precuing or symbolic-compatibility task. Thus, once established, the task-specific procedures remain accessible for use with the specific task from which they were acquired.

Although the task-specific procedures are durable, the transfer of them to related tasks occurs in only limited situations. After three sessions of practice with a vertical stimulus set, changing to a horizontal stimulus set produced complete transfer (Experiment 8A). Thus, this alteration of stimulus orientation that maintained the relative spatial locations apparently did not require abandonment of the previously acquired task-specific procedures associated with the precuing. In contrast, when the orientation of the response set was altered, in addition to that of the stimulus set (the horizontal to vertial-side change in Experiment 8), virtually no transfer was apparent. Similarly, when the orientation was retained but the specific placement of fingers on response keys was altered (the vertical to vertical-side change in Experiment 8), little transfer also was evident. These results, along with our findings that transfer does not occur between overlapped and adjacent placements (Proctor & Reeve, 1988), indicate that the task-specific procedures are sensitive to the specific nature of the response set.

Interestingly, when more extended practice is given, the benefits become more generalizable. Subjects who practiced for 12 sessions with the overlapped hand placement showed a reduced pattern of differential precuing benefits when transferred to the adjacent placement (Experiment 7). This finding is in contrast to the complete reinstatement of the pattern that we found previously when the transfer session occurred after just 3 sessions of practice (Proctor & Reeve, 1988). A similarly diminished pattern of differential precuing benefits was shown by subjects who practiced with the symbolic stimulus set for eight sessions before being transferred to the spatial-precuing task (Experiment 10). This partial transfer was independent of the specific assignment with which practice occurred. The evidence for generalized transfer after extended practice suggests a subsequent stage of skill acquisition beyond that of acquiring task-specific procedures. The possibility of a third stage in which more abstract schema are acquired conforms to the view that there are three distinct stages of skill acquisition (Anderson, 1987; Fitts & Posner, 1967).

V. Conclusions

The review of the literature on S-R compatibility effects indicates an emerging consensus regarding the underlying causes of the effects. Particularly prominent is the view that the mental codings of the stimulus and response sets, and their relation, are at the heart of the effects. This report presents a coding account of S-R compatibility based primarily on spatial-precuing and symbolic-compatibility tasks, but which is consistent with the larger literature on S-R compatibility. The unique aspect of this account is that it has been derived from more complex tasks and thus provides better insight into the nature and role of mental coding. Additionally, the account incorporates changes that occur with practice and specifies the conditions under which such changes are retained and transferred. Our investigations and those of other researchers consistently have spotlighted the central role of mental representations in S-R compatibility effects, thus emphasizing that these effects reflect fundamental cognitive processes.

VI. References

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Authors Note

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Table 1. Stimulus Displays for Each Precue Condition, When the Target Indicates the Left Middle-Finger Response for Hands Placed in a Normal, Adjacent Manner.

	Finger			
Stimulus	LM	LI	RI	RM
	Unprepared			
Warning	+	+	+	+
Precue	+	+	+	+
Target	+			
	Prepared:Hand			
Warning	+	+	+	+
Precue	+	+		
Target	+			
	Prepared:Finger			
Warning	+	+	+	+
Precue	+			+
Target	+			
	Prepared:Neither			
Warning	+	+	+	+
Precue	+		+	
Target	+			

Note. L = left hand; R = right hand; M = middle finger; I = index finger.

Table 2. Example Displays for Experiment 1, with a Prepared:Hand Precue and the Target Indicating the Leftmost Response Location.

Stimuli	Display: Control	Left-Right	Inner-Outer	Alternating
		Version 1		
Warning	++++	++oo	+oo+	+o+o
Precue	++	++	+o	+o
Target	+	+	+	+
		Version 2		
Warning	oooo	oo++	o++o	o+o+
Precue	oo	oo	o+	o+
Target	o	o	o	o

Table 3. Mean RTs (in ms) as a Function of Display Condition, Precue, and Hand Placement in Experiment 1.

Precue	Display: Control	Left-Right	Inner-Outer	Alternating
	Adjacent hand placement			
Unprepared	560	515	501	556
Hand	511	470	454	517
Finger	540	498	462	526
Neither	553	511	476	542
	Overlapped hand placement			
Unprepared	729	690	680	744
Hand	720	704	662	711
Finger	703	683	648	709
Neither	696	664	656	686

Table 4. Stimulus and Response Arrangements for Experiment 2.

Stimulus	+	+
Display	+	+
Left-Right	LM	RM
Placement	LI	RI
Top-Bottom	RI	RM
Placement	LM	LI

Note. L = left hand; R = right hand; M = middle finger; I = index finger.

Table 5. The Precue x Hand Placement Interaction for RTs (in ms) in Experiment 2.

	Precue			
Hand Placement	Unprepared	Hand	Finger	Neither
Left-Right	605	534	530	541
Top-Bottom	657	571	601	579

Table 6. The Interval x Hand Placement Interaction for Percentages of Errors in Experiment 2.

Hand Placement	Interval (in ms)				
	125	375	750	1500	3000
Left/Right	1.8	0.9	1.4	1.8	2.8
Top/Bottom	1.8	2.6	1.8	3.4	2.1

Table 7. Stimulus Displays and Response Arrangements for Experiment 3.

	Display					
Arrangement	Control		Left-Right		Top-Bottom	
Stimulus	+	+	o	+	o	o
	+	+	o	+	+	+
Left-Right Response	LM	RM	LM	RM	LM	RM
	LI	RI	LI	RI	LI	RI
Top-Bottom Response	RI	RM	RI	RM	RI	RM
	LM	LI	LM	LI	LM	LI

Note. L = left hand; R = right hand; M = middle finger; I = index finger.

Table 8. The Precue x Hand Placement Interaction for RTs (in ms) in Experiment 3.

Hand Placement	Precue			
	Unprepared	Hand	Finger	Neither
Left-Right	604	517	513	522
Top-Bottom	664	553	578	565

Table 9. The Display x Hand Placement x Precue Interaction for Percentages of Errors in Experiment 4.

	Precue			
Hand Placement	Unprepared	Hand	Finger	Neither
	Display Together			
Together	1.5	3.1	1.6	2.5
Separated	2.7	2.7	2.5	2.8
	Display Separated			
Together	2.2	1.5	2.5	3.3
Separated	1.6	1.6	2.2	2.2

Table 10. The Precue x Interval Interaction for Errors in Experiment 4A.

	Interval (in ms)				
Precue Condition	0	375	750	1500	3000
Unprepared	2.3	4.2	2.6	2.6	5.2
Hand	1.0	4.8	2.9	2.9	2.6
Finger	5.3	4.3	3.5	1.2	1.6
Neither	4.6	3.4	4.3	4.3	3.6

Table 11. The Precue Condition x Display Orientation x Response Orientation Interaction for the Percentage of Errors in Experiment 5.

	Precue			
Response Orientation	Unprepared	Hand	Finger	Neither
	Horizontal Display			
Horizontal	1.8	2.9	3.1	3.9
Vertical	3.3	6.3	5.3	3.3
	Vertical Display			
Horizontal	3.1	4.3	4.0	4.1
Vertical	3.9	5.0	3.8	5.3

Table 12. Mean RTs (in ms) as a Function of Session and Precue in Experiment 6.

	Precue			
Session	Unprepared	Hand	Finger	Neither
1	539	494	517	542
2	505	463	467	486
3	500	453	451	466

Table 13. Mean RTs (in ms) as a Function of Precue and Retention Group in Experiment 6.

	Precue			
Retention Group	Unprepared	Hand	Finger	Neither
Immediate	484	432	440	448
Delayed	504	462	460	477

Table 14. Mean RTs (in ms) from the Transfer Tests (Sessions 13-16) as a Function of Session and Precue in Experiment 7.

	Precue			
Session	Unprepared	Hand	Finger	Neither
		Practice Sessions		
1	644	626	612	593
12	507	457	452	464
		Transfer Sessions		
13	512	468	470	487
14	487	444	446	449
15	462	429	425	429
16	464	421	429	427

Note. The practice sessions involved the overlapped hand placement, whereas the transfer sessions involved the adjacent hand placement.

Table 15. The Precue x Arrangement Interaction for RTs (in ms) from the Transfer Session in Experiment 8.

Practice Arrangement	Precue: Unprepared	Hand	Finger	Neither
Horizontal	613	558	582	609
Vertical	618	557	582	584
Vertical-Side	547	502	489	507

Table 16. Mean RTs (in ms) as a Function of Practice and Precue for the Transfer Session in Experiment 8A.

	Precue			
Practice	Unprepared	Hand	Finger	Neither
Horizontal	503	469	473	480
Vertical	512	471	471	487

Table 17. Mean RTs (in ms) as a function of Session and Assignment in Experiment 10.

	Session							
Assignment	1	2	3	4	5	6	7	8
OozZ	616	552	537	530	539	537	534	534
OzoZ	732	633	613	593	598	586	586	595

Table 18. Mean RTs (in ms) as a Function of Practice with Symbolic Stimuli and Precue on the Spatial-Precue Transfer Task in Experiment 10.

	Precue			
Practice	Unprepared	Hand	Finger	Neither
OozZ	508	474	479	502
OzoZ	482	457	456	478

Figure Captions

Figure 1. Mean RTs as a function of preparation condition (precue and hand placement for the display-together condition in Experiment 4.

Figure 2. Mean RTs as a function of preparation condition (precue) and hand placement for the display-separated condition in Experiment 4.

Figure 3. Mean RTs as a function of preparation condition (precue, and display for Experiment 4A.

Figure 4. Mean RTs as a function of precue and response orientation for Experiment 5.

Figure 5. Mean RTs as a function of display orientation and response orientation for Experiment 5.

Figure 6. Mean RTs as a function of assignment and session in Experiment 9.

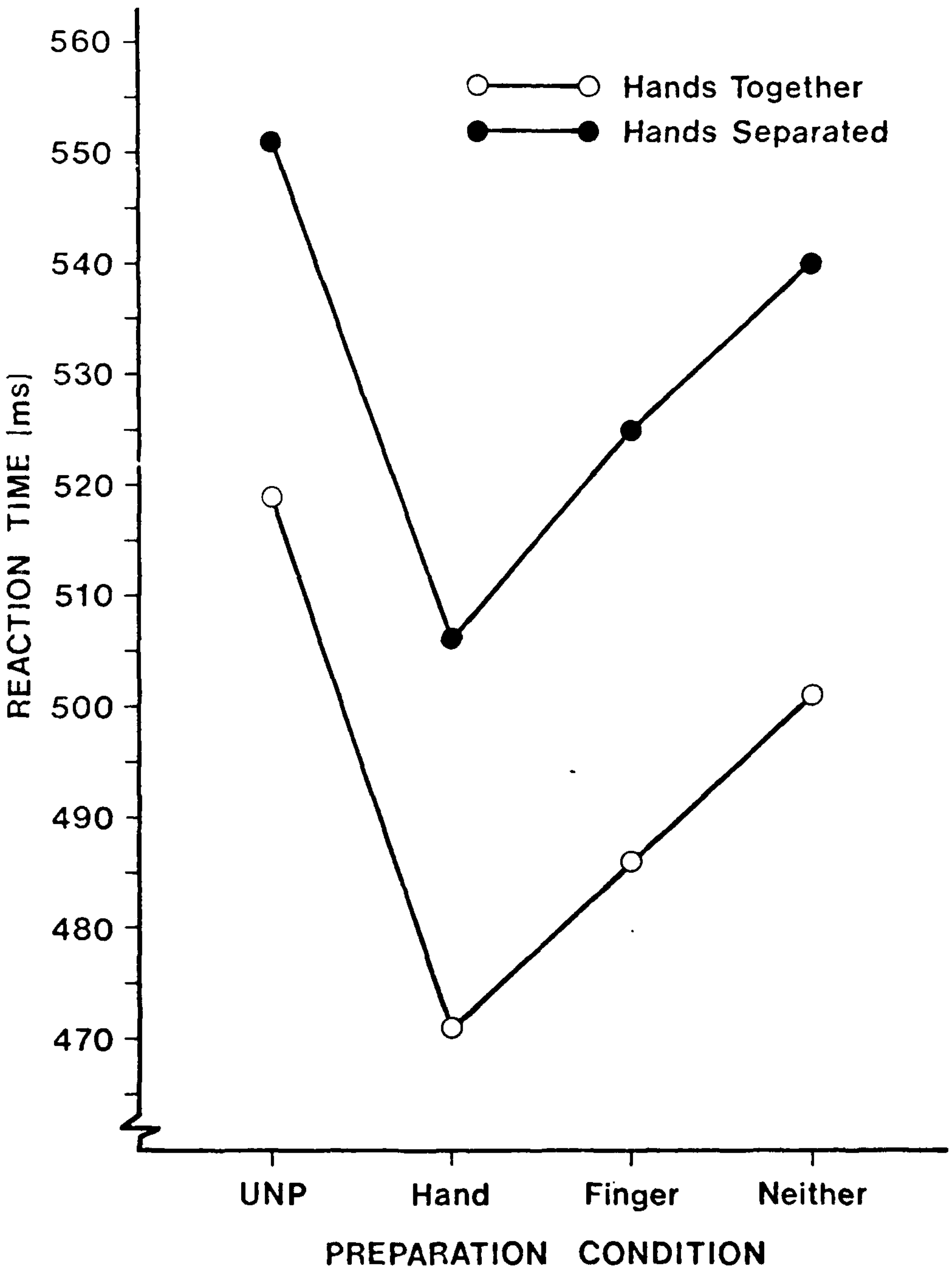

560
550
540
530
520
510
500
490
480
470
REACTION TIME (ms)
Hands Together
Hands Separated
UNP
Hand
Finger
Neither
PREPARATION CONDITION

Figure 1

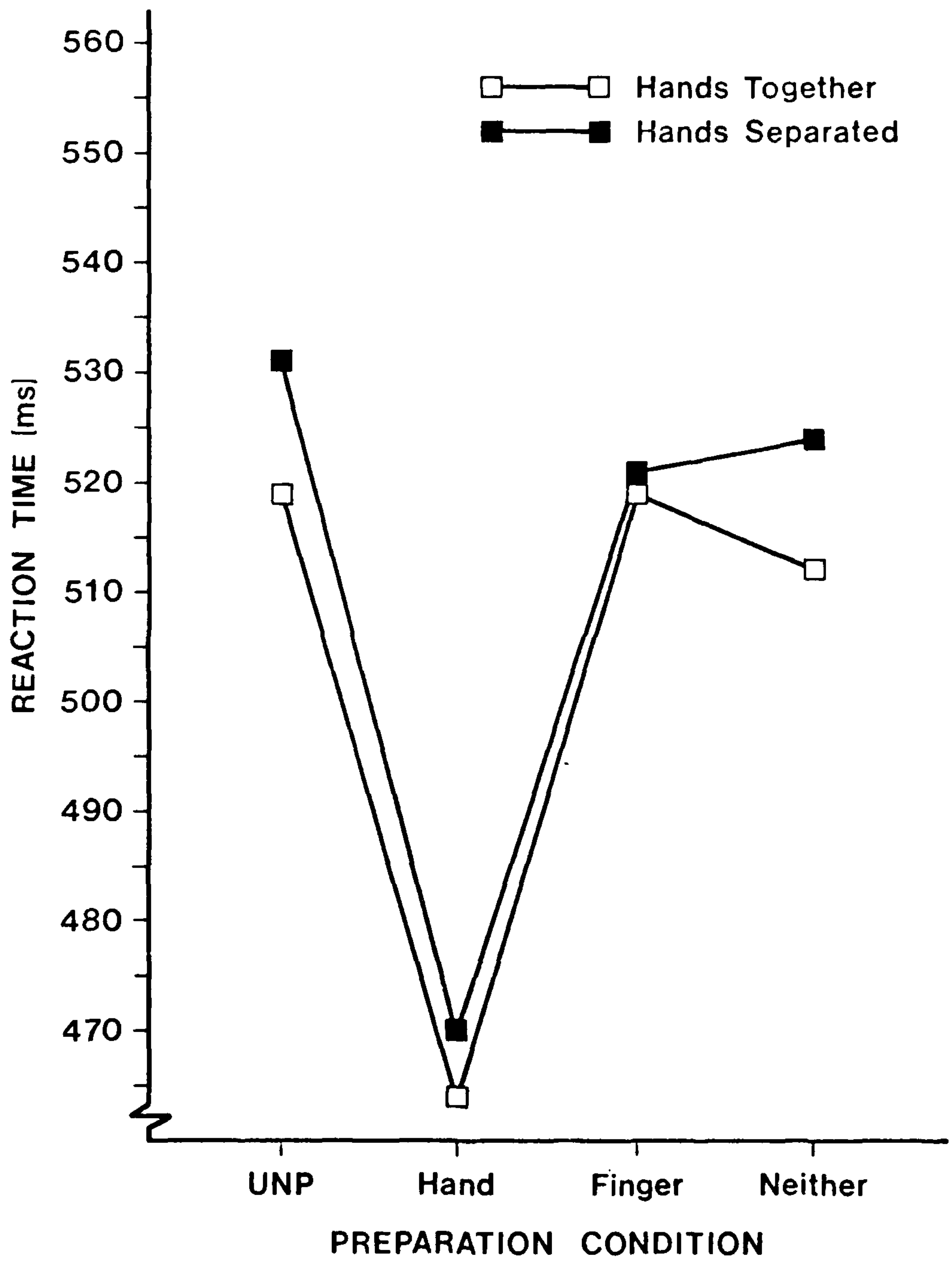
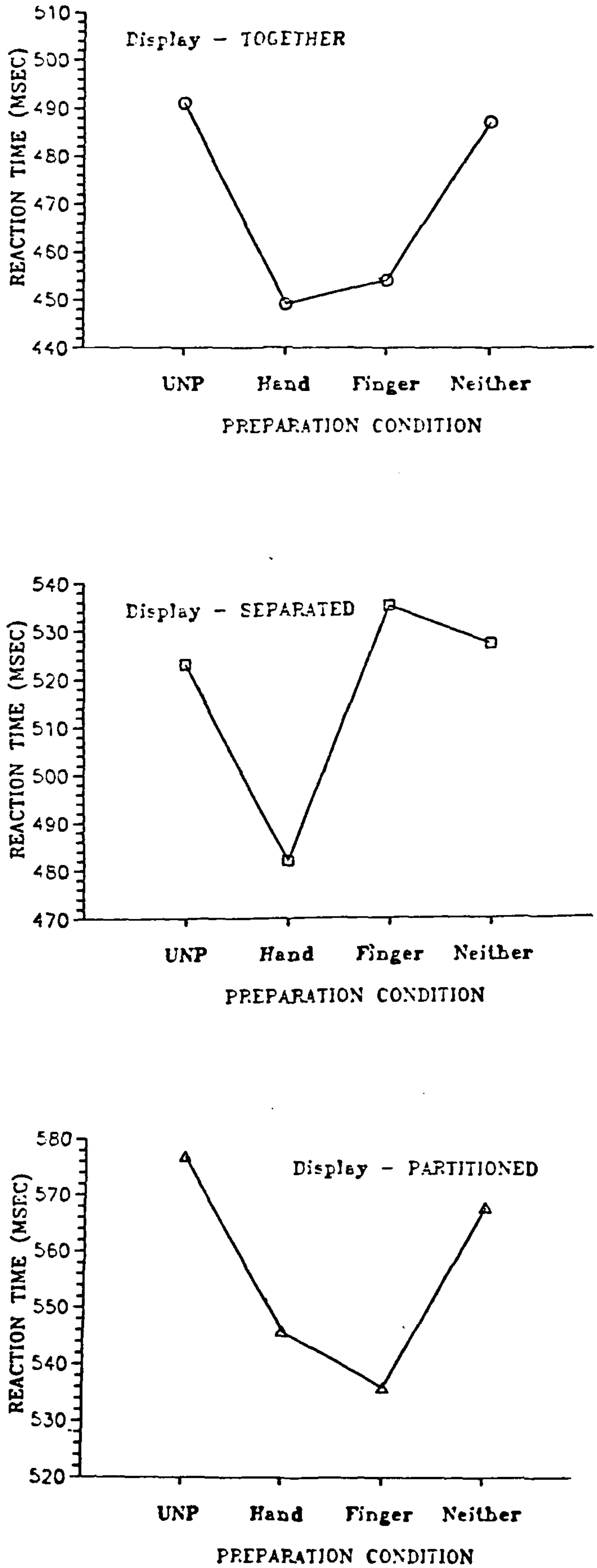

Hands Together
Hands Separated
560
550
540
530
520
510
500
490
480
470
REACTION TIME (ms)
UNP
Hand
Finger
Neither
PREPARATION CONDITION

Figure 2



510
500
490
480
470
460
450
440
REACTION TIME (MSEC)
Display - TOGETHER
UNP
Hand
Finger
Neither
PREPARATION CONDITION
540
530
520
510
500
490
480
470
REACTION TIME (MSEC)
Display - SEPARATED
UNP
Hand
Finger
Neither
PREPARATION CONDITION
580
570
560
550
540
530
520
REACTION TIME (MSEC)
Display - PARTITIONED
UNP
Hand
Finger
Neither
PREPARATION CONDITION

Figure 3

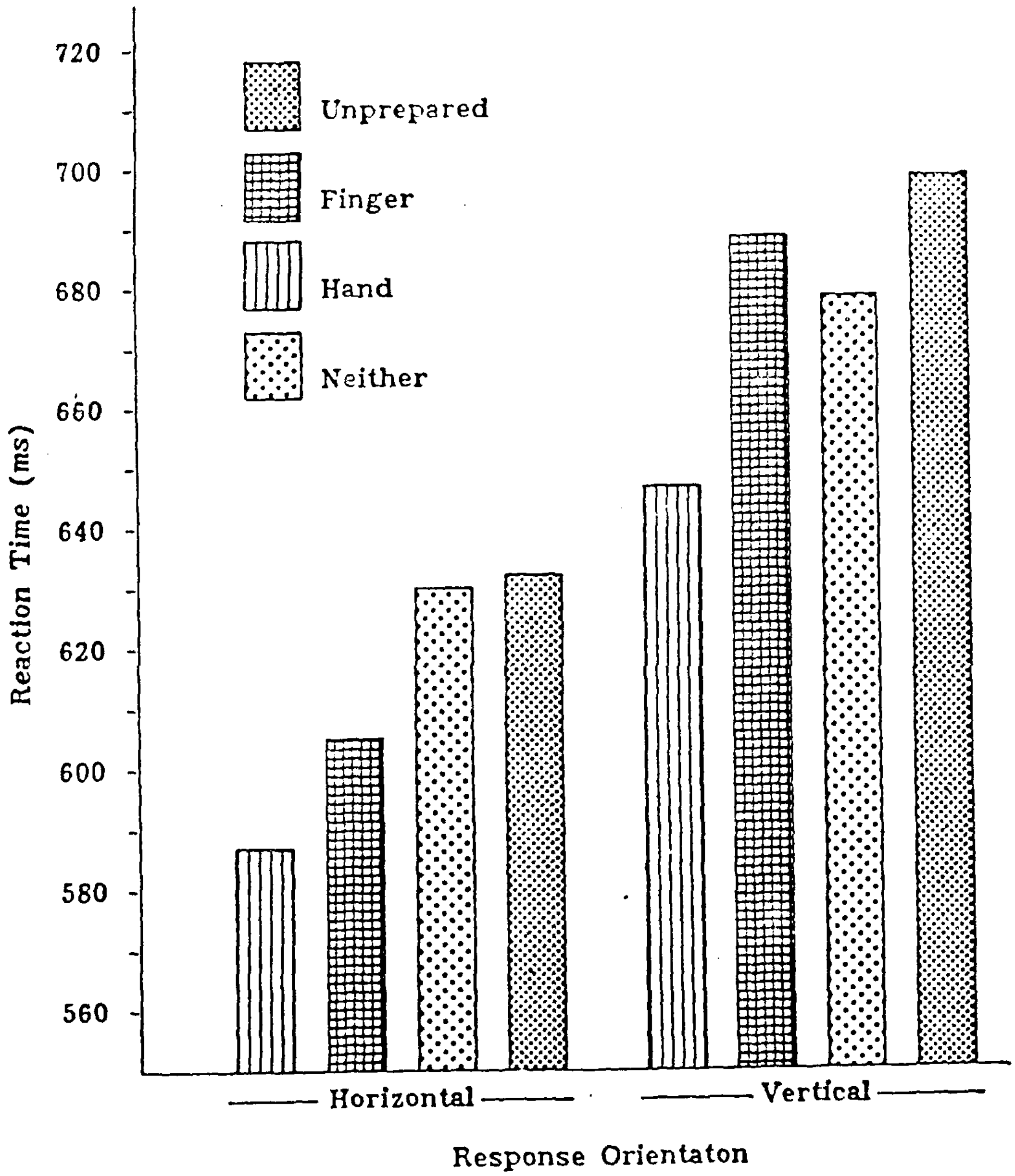

720
700
680
660
640
620
600
580
560
Reaction Time (ms)
Unprepared
Finger
Hand
Neither
Horizontal
Vertical
Response Orientaton

Figure 4

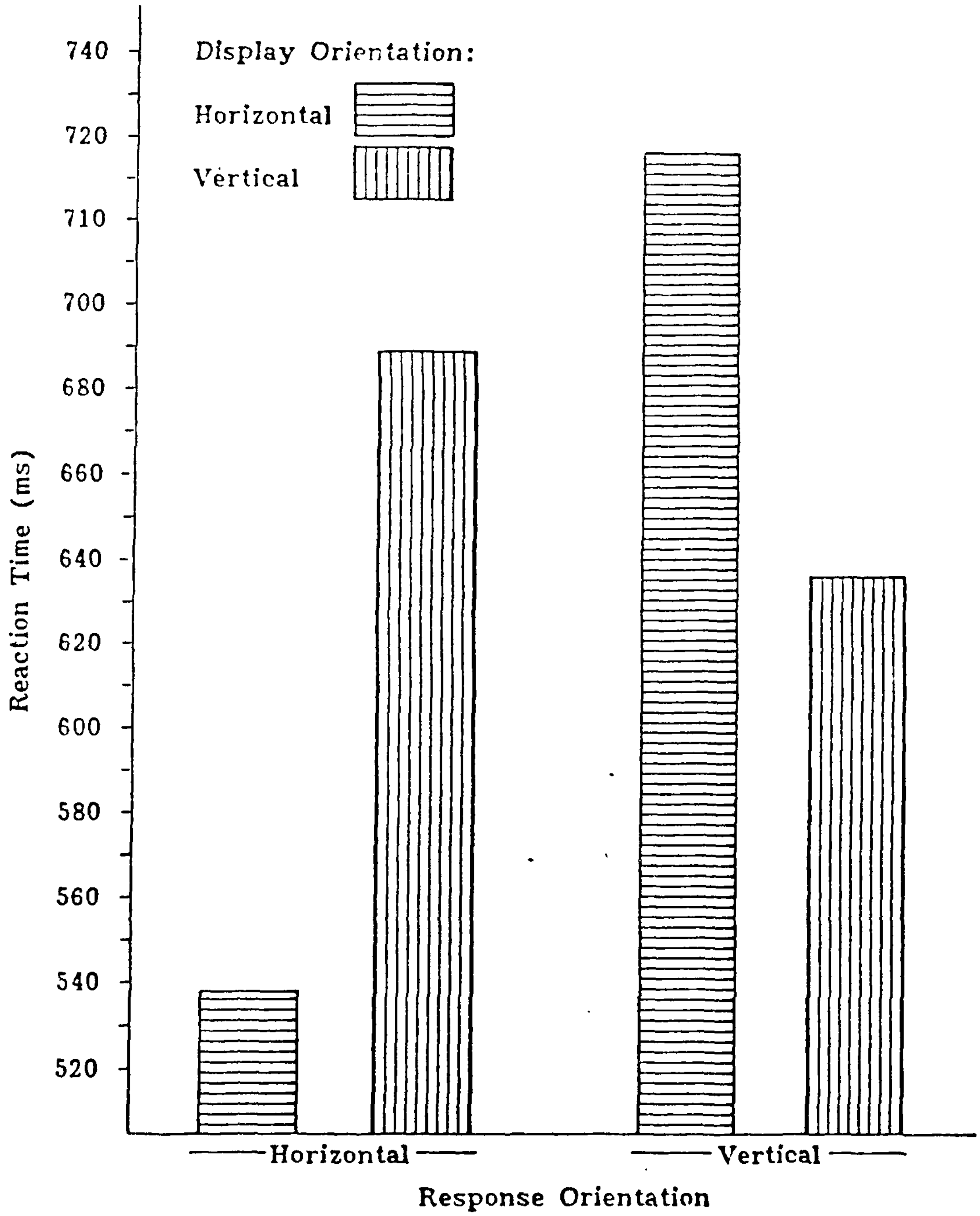

Display Orientation:
Horizontal
Vertical
740
720
710
700
680
660
640
620
600
580
560
540
520
Reaction Time (ms)
Horizontal
Vertical
Response Orientation

Figure 5

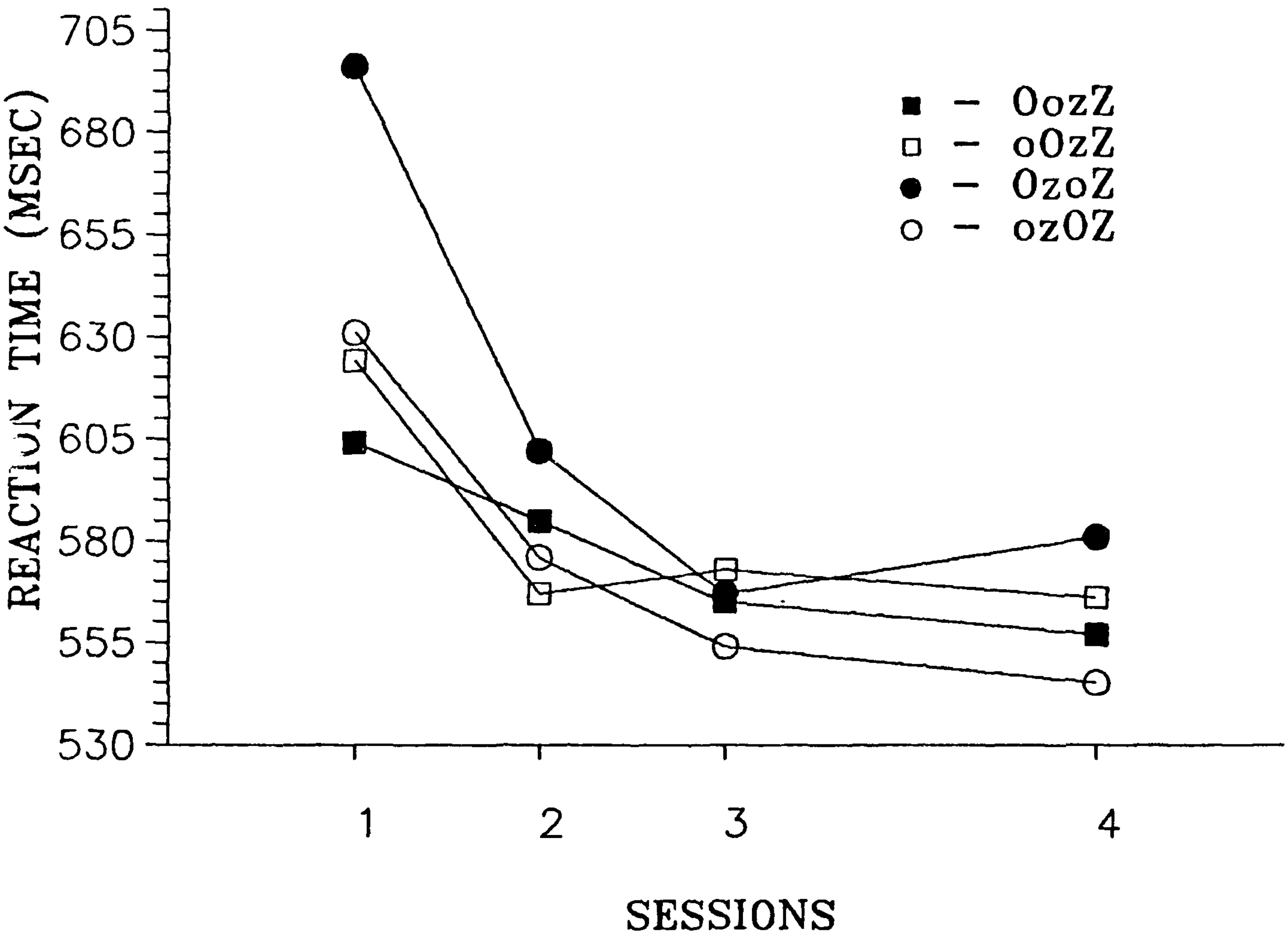

705
680
655
630
605
580
555
530
REACTION TIME (MSEC)
■ – OozZ
□ – oOzZ
● – OzoZ
○ – ozOZ
1
2
3
4
SESSIONS

Figure 6

Appendix 1

Contents of and Contributors to

Stimulus-Response Compatibility: An Integrated Perspective

Robert W. Proctor and T. Gilmour Reeve

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